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Combining Policymaking Tools for Green Transition: Eco-efficiency Benchmarking and Club Convergence

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Abstract

This study examines the eco-efficiency performance of green energy transitions in 45 high-emission countries (1995–2022), focusing on convergence in policymaking. Using hybrid window data envelopment analysis (WDEA) models, eco-efficiency was evaluated for non-renewable energy (NRES), renewable energy (RES), and mixed sources. Inputs included capital, labor, and electricity generation; outputs were GDP (desirable) and CO_2 and CH_4 emissions (undesirable). Efficiency averaged 76.04% (RES), 74.25% (NRES), and 73.61% (mixed). Conditional convergence analysis revealed countries with similar conditions converge to unique steady states, highlighting the need for harmonized energy standards, therefore investments in green technologies can reduce emissions and electricity generation costs.

Keywords: *hybrid window DEA, club convergence, imergeclub, logtreg, Log t regression test, energy sectors*

JEL Codes: *013; Q42; Q48*

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1. Introduction

Green transition in energy sectors is at stake due to the current *multi-crisis* phenomena, such as energy price volatility, inflation pressures, and geopolitical conflicts (Antoniades et al., 2020; Bhattacharyya, 2019; Halkos & Argyropoulou, 2021; Halkos & Aslanidis, 2023a, 2023b, 2024; IEA, 2023; Mohammadian et al., 2022). More specifically, the Russo-Ukrainian conflict that begun in 2022 escalated into a series of events, especially in the energy sector. For example, the EU has delivered the REPowerEU Plan in order to be less reliant to fossil fuels and pressure EU countries to adopt renewables (Brown & Jones, 2024; EC, 2022).

Multi-crisis can derail global efforts to conclude sustainable development goals (SDGs) (especially SDG7) under the scope of Agenda 2030 and *Net-zero* economy in line with Agenda 2050. It is interesting that the countries in the European Union, the rest countries of Organization of Economic Cooperation (OECD), and the group of countries known as BRICS (i.e., Brazil, Russia, India, China, and South Africa) are not only the main antagonists in clean energy transition, but also the most polluting ones (Addis & Cheng, 2023; Cheng et al., 2023; Vaillant et al., 2024; Yousefi et al., 2023). In essence, the OECD, EU, and BRICS countries have the most energy-intensive-trade-exposed sectors (EITE).

The *COP28 conference* in United Arab Emirates necessitated for green transition by tripling renewables and by doubling energy efficiency, complementing therefore countries' pledge to Agenda 2030 (IRENA, 2024). However, OECD (2023) alerted that global action ought to be taken according to climate change commitments under SDGs scope, especially focusing on the high costs of inaction regarding the transition from fossil fuels to renewables. IEA (2023) interprets the "*end of fossil fuel era*" not as the absolute end in fossil fuel investments, but the lower spending at this energy sector. Therefore, it is imperative that countries monitor their performance in energy sectors and potential convergence dynamics, aiming to unveil promising collaborations and partnerships.

OECD countries produce on average twice as much CO_2 emissions (per capita) as the global average (IEA, 2024; Karlilar Pata & Balcilar, 2024). Stable energy supply can be accomplished by expanding renewable energy sources (RES) production capacity, which should be a development strategy priority for all OECD countries. Besides, the development of clean technologies for power generation can lead to a gradual shift away from fossil fuels and thus contribute to reducing emissions and the caused environmental damage in line with sustainable energy development pathways. (Iddrisu & Bhattacharyya, 2015).

A diverse Net Zero pathway of nationally determined contributions (NDCs) is blueprinted in BRICS. It has been observed that BRICS make efforts to reduce their energy and emissions intensity in order to adhere to climate change mitigation actions, even though their economies are highly dependent to fossil fuels (Alam et al., 2024; Gerasimchuk et al., 2019; Ramluckun et al., 2024). Net Zero commitments have been emphasized in BRICS group, first South Africa NDC is in tandem with Paris Agreement proposal for being Net Zero by 2050, followed by the Brazilian, Russian, and Chinese NDCs which are aiming to year 2060, whereas only India has a longer NDC target for 2070 (ILO, 2022).

China is a significant player in BRICS. Rapid Chinese growth is linked to over-exploitation of natural resource stocks, for instance China is the largest emitter and energy-consuming country in the world (Wang et al., 2013). Especially in China, vast decarbonization action have taken place in order to ameliorate air quality and health standards. Nevertheless *carbon emissions* in China are expected to reach a peak in 2026, with a one-third reduction by 2040, while a similar pathway is blueprinted regarding *energy use*, peaking by 2030 but with one-fifth reduction by 2050 (DNV, 2024). China is influenced by uncoordinated economic growth, but technological innovation has positively affected the industrial organization and development (Tao et al., 2024).

In the EU, the *European Green Deal* aspires to make Europe the first Net-Zero continent at the point of Agenda 2050 (EC, 2019). A plethora of energy-specific policies have been taken into account by all EU countries such as the climate change mitigation strategies through Emission Trade Schemes (ETS) regarding carbon trade agreements (EC, 2024) and the “Fit-for-55” package regarding the reduction of emissions at least 55% by 2030 based on 1990 levels (EC, 2021). It ought to be mentioned that the previous goal was only 40% reduction by 2030, so the "Fit-for-55" goals is undoubtedly a significant but challenging target. According to Borowiecki et al. (2023) the European strategies regarding green energy transition are in line with the efforts on building *energy security* in Europe.

We found a research gap in the energy-related sectors regarding the combination of eco-efficiency benchmarking and club convergence methodologies. In order to cope with this void in literature, we propose a novel approach that utilizes the *hybrid window data envelopment analysis* (hybrid WDEA) and then the extracted eco-efficiencies are the inputs to a *club clustering* technique, aiming to create groups of countries with common clean energy transition pathways. The structure of the present research commences with Section 2 is devoted to the literature of benchmarking methodologies and club clustering. Section 3 presents the proposed methodology for both techniques followed by Section 4 that comprises the main results and discussion. Last but not least, Section 5 concludes the paper and offers policy implications regarding future strengthening of eco-efficiency club convergence. Therefore we pose some research questions (RQ):

RQ1: *Is there difference between the adoption of RES in the overall eco-efficiency score among the 45 most polluting countries?*

RQ2: *How can club clustering convergence untangle the hidden national incapacities regarding the achievement of green transition?*

RQ3: *Is there divergence between the EU, OECD rest countries, and BRICS?*

2. Literature review

In the literature, the efficiency of decision-making units (DMUs) can be measured either through stochastic frontier analysis (SFA) or data envelopment analysis (DEA), both of which have their own merits and disadvantages (Coelli et al., 2005). In the present research we employ a DEA-based technique and in general efficiency in DEA takes values between zero (i.e., inefficiency) and unity (i.e., efficiency).

Traditional DEA is adequate for cross-sectional analysis, but Charnes et al. (1984) expanded the traditional DEA into *window DEA* (WDEA), which employs panel data modelling by resorting to moving average formulae. WDEA has two important characteristics, on the one hand, each window is treated like a novel DMU, on the other hand, there is comparison between each DMU and between its own performance (Halkos & Polemis, 2018).

In DEA methodologies, as Tone (2004) advocated, there are two ways to exploit the impacts of inputs and outputs, i.e. either by radial or non-radial methodology. Radial methodology has been widely used in the most common DEA studies, for example both models proposed by Charnes et al. (1978) (CRR model) and Banker et al. (1984) (BCC model). The radial methodology ignores the influence of slacks, leading to potential under-evaluation of the results (Avkiran et al., 2008). The non-radial methodology[1] has different applications in the DEA literature, as for instance, the slack-based measure (SBM) by Tone (2001). Nevertheless, non-radial approach might overlook significant aspects of the radial methodology, ushering to such as the neglection of proportionality (Avkiran et al., 2008). In order to cope with these challenges, one might utilize the *hybrid DEA* that considers both radial and non-radial modelling aspects (Tone, 2004).

The dealing with undesirable outputs and the choice of disposability are two core prerequisites of DEA. First, there is a plethora of coping with undesirable outputs, such as data transformations (Førsund, 2018; Halkos & Petrou, 2019; Liu et al., 2010). Second, in DEA the selection of weak disposability and null-jointness property can be employed when the modelling includes undesirable outputs (Färe & Grosskopf, 2004, 2009). The above issues show that if the minimization of pollution can be done through technological achievement, the choice of weak disposability is proper (Halkos & Polemis, 2018). On the contrary, this is debatable according to Kuosmanen (2005), Kuosmanen and Podinovski (2009), Chen (2013), and Mehdiloo and

[1] For interesting applications of non-radial models, please check the publications of Zhou et al. (2007), Chang et al., (2013), and Zhang and Cui (2020).

Podinovski (2019). Essentially, Mehdiloo and Podinovski (2019), utilized different techniques in order to showcase when weak or strong disposability is more applicable. Moreover, the DEA methodology has been applied in OECD, EU, or BRICS countries in order to monitor the efficiency performance, or when considering ecological aspects: eco-efficiency.

2.1. Benchmarking in energy sectors

Efficiency performance can present the main opportunities and weaknesses either in countries or sectors level. The recent literature review regarding energy-related studies and DEA-based techniques are presented in Appendix A Table A.1, the following text summarizes some of the main results in these research studies.

Wang et al. (2013) monitored 29 Chinese region regarding their energy and environmental performance via WDEA in the period 2000 – 2008, as a result, they found east area has the greatest efficiency against the western regions. Apergis et al. (2015) utilized a two-stage modelling, first a SBM-DEA model followed by an Generalized Linear Mixed Model – Markov Chain Monte Carlo (GLMM-MCMC) analysis in 20 OECD countries, overall they found that EU countries had the highest efficiency against North American Free Trade Agreement (NAFTA), G7, and Asian Tigers (i.e., Hong Kong, Singapore, South Korea, and Taiwan).

Camioto et al. (2016) compared BRICS and G7 countries based on SBM-DEA, window analysis and Tobit model, the results showed that G7 had greater efficiency than BRICS, and among the BRICS countries Brazil performed better in terms of energy efficiency. Similar results were presented in Camioto et al. (2015). Additionally, Guo et al. (2017) applied a dynamic DEA in OECD and China, concluding that the average performance was 78% in the period 2000 – 2010, whereas the efficient countries were Belgium, Denmark, Ireland, Israel, Japan, Netherlands, Switzerland, United Kingdom, and United States.

Moutinho et al. (2017) employed an output-oriented (CRS & VRS) DEA followed by a quantile regression in 26 European states during 2001 and 2012, their results presented that environmental tax revenues might aggravate the eco-efficiency performance. Ouyang and Yang (2020) performed a multiplicative network DEA in 27 OECD countries with United States and New Zealand being the overall efficient countries.

Halkos & Aslanidis (2023, 2024) delved into productivity either by comparing G20 countries or EU – 27 performance on environmental and geopolitical issues. Halkos & Aslanidis (2023) showed that geopolitical status of Indonesia, Mexico, Russia, China, and India is driven by energy-related eco-productivity. Moreover, Halkos & Aslanidis (2024) measured eco-productivity in EU-27 green transition, the top-performing countries were Cyprus, UK, Netherlands, France, Ireland, and Malta. Additionally, Halkos & Bampatsou (2022) employed two DEA models, i.e., a static and a dynamic, in order to measure the impact of electricity generation on productivity performance, in which Luxembourg, Sweden, Malta, Netherlands, and Denmark had the top eco-efficiency performances among the EU-28 countries.

Iram et al. (2020) calculated the efficiency performance in 26 OECD countries during 2013 – 2017, in this publication the most efficiency countries were Brunei, Australia, Singapore, and Hong Kong. Mamghaderi et al. (2023) evaluated the eco-performance of 27 OECD countries during the period 2000 – 2017 based on SBM-DEA model followed by a Global Malmquist-Luenberger Index with the United Kingdom being the most efficient country, whereas Lithuania the least efficient.

The above DEA-based techniques showcase the scientific interest regarding the efficiency performance measurement, especially when dealing with undesirable outputs. It can be also argued that efficiency scores were strengthened by additional analysis such as other econometric methodologies as in Apergis et al. (2015), Camioto et al. (2016), Camioto et al. (2016), and Mamghaderi et al. (2023) to name but a few. In this way, we are going to present an interesting methodology in the following section that can be combined with efficiency performance in order to unveil potential interrelations between the studied countries.

2.2. *Energy convergence based on the club test theory of Phillips and Sul*

The energy sector plays a central role in the realization of the SDGs, and the interest of scientists has increasingly focused on energy research and energy convergence issues in recent years through the convergence algorithm developed by Phillips and Sul (2007).

In this context, based on the assumption that uncoordinated energy consumption between regions may aggravate economic development and the attainment of energy strategic targets, Bangjun et al. (2023) attempt to investigate the trend and factors affecting the convergence of per capita energy consumption. Therefore, they investigate the convergence trend of per person energy consumption of two-hundred forty-three national-level Chinese cities for the period from 2005 to 2019. With their empirical approach based on the club test theory of Phillips and Sul (2007), they find that there are four converging clubs and one diverging club.

The trend of convergence in per person energy consumption is also examined by Ivanovski et al. (2018) using the same methodological approach, both at the Australian states (New South Wales, Northern Territory, Queensland, South Australia, Tasmania, Victoria and Western Australia) and at the sectoral focus (e.g., agriculture, electricity etc.) for the period 1990 to 2016. The empirical analysis shows different patterns of energy convergence for eight of the nine sectors in all countries. Therefore, the development of a single energy policy may not lead to the desired results in all states and economic sectors.

Apergis and Christou (2016), based on the same methodology as Phillips and Sul (2007), examined the convergence trends in energy productivity of 31 countries for the period from 1972 to 2012. According to the results of their empirical analysis, there is no full convergence of the sample countries, and the existence of a number of subgroups (clubs) is confirmed. However, they point out that there is a long-term trend towards convergence in energy productivity, which is related to the implementation of appropriate energy policies that can lead to a uniform convergence model.

The same convergence methods of Phillips and Sul (2007) is applied by Pinar (2024) in his attempt to understand convergence patterns in renewable energy-related technological advancements for a sample of 90 countries and for the period from 1993 to 2018. According to the results, there is no absolute convergence for all 90 countries, and the existence of two convergence clubs with the most and least innovative countries is confirmed. The analysis also extends to the study of convergence factors, through which you outline the profile of countries that are most likely to converge with the most innovative countries.

Saba and Ngepah (2022) used Phillips and Sul's convergence algorithm to audit the convergence trend in renewable energy-driven consumption for the case of 183 nations and for the period from 2000 to 2018. The group of countries was divided into five areas. Specifically, the study focused on Sub-Saharan Africa, the Middle East and North Africa, Europe and Central Asia, East and South Asia and the Pacific, and America, with the formation of 6, 2, 2, 5 and 3 final clubs, respectively, converging on the consumption of energy from renewable sources and thus on the goal of environmental sustainability. Next is the section regarding methodology of combining the two aforementioned methodologies.

3. Material and Methods

The present research retrieved data have from WBG (2022) for all variables except electricity generation that is extracted from the "our world in data" (OWID, 2024) database and span throughout the period 1995 - 2022. The DMUs are forty-five countries[2] that belong either to the Organization of Economic and Development (OECD), European Union (EU), or BRICS economies, the choice of which has been dictated strictly by data availability. More information about the studied countries is presented at Appendix B Table B.1 regarding the surface area, overall population, life expectancy, and annual growth for comparison reasons. The structure of the present study is illustrated at Figure 1.

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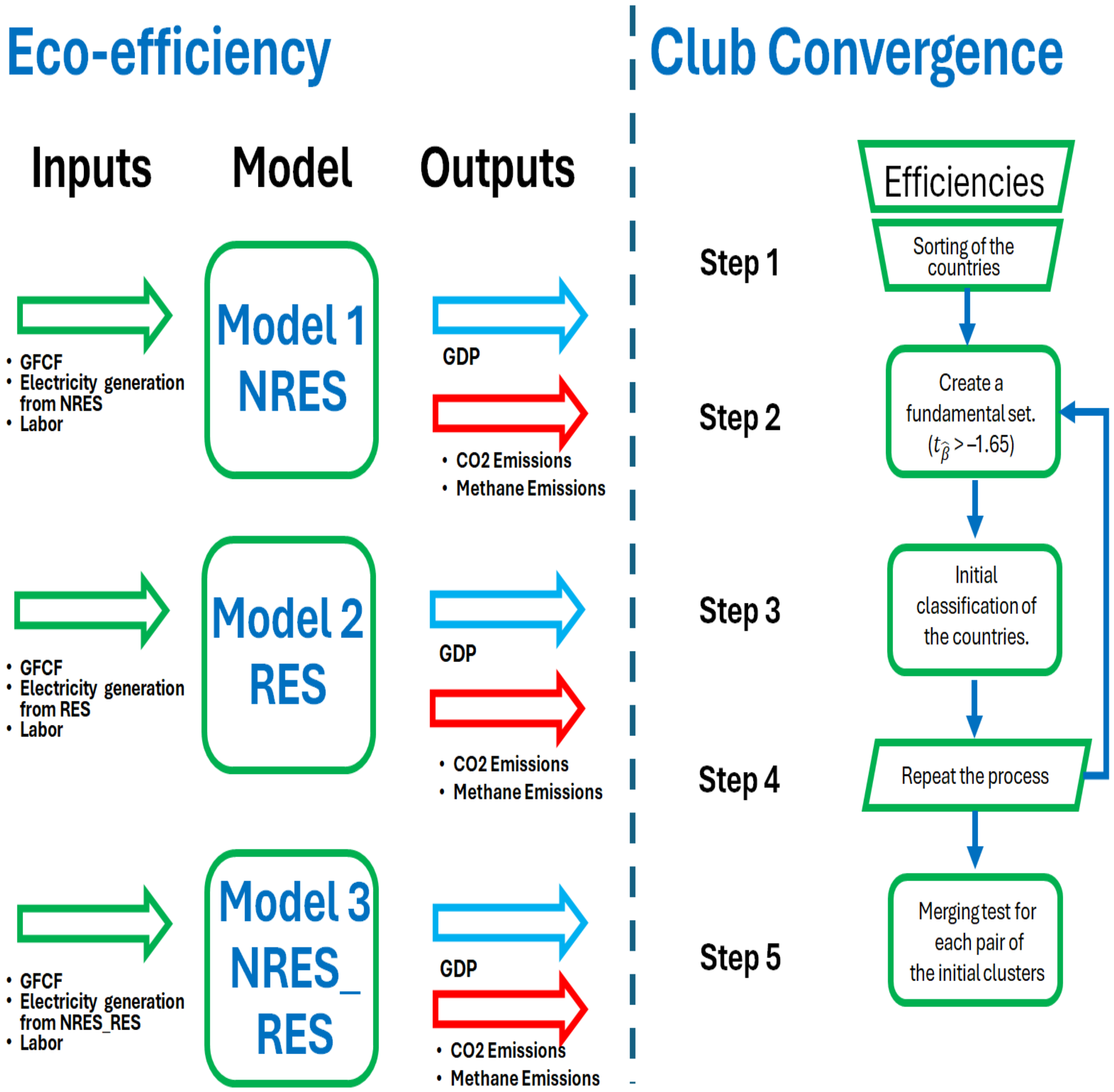
[2] Australia, Austria, Belgium, Brazil, Bulgaria, Canada, Chile, China, Colombia, Costa Rica, Croatia, Cyprus, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, India, Ireland, Israel, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Mexico, Netherlands, New Zealand, Poland, Portugal, Romania, Russia, Slovakia, Slovenia, South Africa, South Korea, Spain, Sweden, Switzerland, Türkiye, United Kingdom, United States.

Figure 1: The structure of our research



We utilize hybrid WDEA methodology for the eco-efficiency estimation in the green energy transition of 45 EITE economies. Next in order we categorize these countries' eco-efficiency results based on the log t regression method in order to create potential clusters that show club convergence. This is the first time, to our knowledge, that WDEA results are associated with log t technique. However, Sun et al. (2020) have explored this networking of Malmquist DEA results with log t regression, resulting in the creation of clubs regarding their environmental productivity. In addition, Bai et al. (2019) evaluated carbon productivity with the SFA method and afterwards they performed log t algorithm in order to monitor how club convergence respecting CO_2 efficiency.

Table 1: Descriptive statistics

	Min	Mean	Max	STD
INPUTS				
GFCF (Current USD * 10^9)	0.54	288.11	7539.64	739.93
Labor (Total *10^6)	0.14	44.92	781.80	128.50
Electricity Generation (GWh)				
Model NRES	58.41	218,613.93	3,782,824.22	547,760.47
Model RES	--	155,177.23	6,306,489.87	557,234.79
Model NRES_RES	326.00	373,949.84	8,848,730.00	912,715.83
OUTPUTS				
CO_2 emissions (kt)	1,352.30	524,099.82	12,015,393.05	1,391,888.96
Methane emissions (kt of CO_2 equivalent)	184.77	98,073.63	1,204,466.06	210,841.32
GDP (Current USD* 10^9)	3.46	1,162.04	25,439.70	2,701.00
CHARACTERISTICS				
Period	1995 - 2022			
No. of DMUs	45 countries			
No. of Observations	1260			

We monitor three models, which have three inputs and three outputs. The descriptive statistics of the variables are presented at Table 1. The input variables are: (i) labor as number of employees; (ii) gross-fixed-capital-formation (GFCF) in current USD; and (iii) electricity generation measured in GWh. Regarding the electricity generation, we have calculated the share of non-renewable (NRES) and renewable (RES) energy sources generation from the World Bank database, but due to lack of data availability regarding electricity generation we have retrieved the aggregate values data from OWID. Finally, we are going to compare eco-efficiencies of all models in order to observe how RES can impact the overall eco-efficiency.

In addition, the desirable output is gross domestic output in current USD and the undesirable outputs are carbon dioxide (CO_2) emissions in kt and methane emissions in kt of CO_2 equivalent. Regarding all models, the desirable outputs have influence on the desirable output in a separable way, whereas there is non-separable way between the production of the desirable output with the undesirable outputs.

Table 2: Correlation matrix

	GFCF	Labor	NRES	RES	NRES_RES	CO_2	CH_4	GDP
GFCF								
Labor	0.592**							
NRES	0.827**	0.344**						
RES	0.753**	0.829**	--					
NRES_RES	0.956**	0.713**	--	--				
CO_2	0.895**	0.801**	0.731**	0.879**	0.976**			
CH_4	0.693**	0.869**	0.578**	0.782**	0.825**	0.862**		
GDP	0.941**	0.445**	0.930**	0.528**	0.881**	0.787**	0.629**	

** Correlation is significant at the 0.01 level (2-tailed).

The correlation Table 2 shows that all variables have positive relations with the others. More specifically, regarding the inputs, labor has feeble correlation with GFCF and NRES. Moreover, both labor and GFCF have strong liaisons to electricity generation for all three models, especially between GFCF and NRES_RES there is almost linear relation. Moving on to the outputs, CO_2 has very strong correlation with CH_4, and GDP has just strong interconnections with both GHGs.

Next in order, an important issue in hybrid WDEA is the choice of window width. It is common practice to utilize window width of three years, because it allows for accurate comparisons (Asmild et al., 2004; Halkos & Polemis, 2018; Halkos & Tzeremes, 2009, 2014; Vlontzos & Pardalos, 2017). It has been also discussed the issue of choosing different window widths subjectively and not objectively as done in Kyrgiakos et al. (2021) and Lin et al. (2018). We utilize window width for five years in order to grasp the meso-term impact of green policies, additionally, we have checked also the width 3 but the results were not of a marginal significance to the manuscript, therefore we have chosen the width 5 as a common width in energy sectors. Having in mind the window width 5 as the basis for the window analysis we move forward to the specifications of the hybrid WDEA model.

3.1. Mathematical modelling of hybrid DEA

First, we have formulated the WDEA technique as in Tone (2004), Cooper et al. (2007, p.107-110) and Halkos & Polemis (2018, p. 337-338). We show that our model has $n = 45$ DMUs, with $\mathcal{k} = 3$ inputs, and $\ell = 3$ outputs in the $\mathbb{R}_{+}^{\mathcal{k}+\ell}$ the Euclidean space. Essentially, we need the matrices of inputs and outputs as $X \in \mathbb{R}_+^{k \times n}$ and $Y \in \mathbb{R}_+^{\ell \times n}$ respectively. Accordingly, the WDEA input and output matrices can be further categorized with radial and non-radial elements, the radial part is illustrated as $X^R \in \mathbb{R}_+^{k_1 \times n}$ and $Y^R \in \mathbb{R}_+^{\ell_1 \times n}$, whereas the non-radial elements as $X^{NR} \in \mathbb{R}_+^{k_2 \times n}$and $Y^{NR} \in \mathbb{R}_+^{\ell_2 \times n}$. Please have in mind that both parts equal the initial categorization as $k = k_1 + k_1$ and $\ell = \ell_1 + \ell_2$. Leading to the matrices as in relation (1):

$$X = \binom{X^R}{X^{NR}} \text{ and } Y = \binom{Y^R}{Y^{NR}} \tag{1}$$

We show the radial and non-radial elements with “R” and “NR”. The production possibility set (P) is presented in relation (2) under the assumption of constant-returns-to-scale:

$$P = \{(x, y) | x \geq X\lambda, \quad y \leq Y\lambda, \quad \lambda \geq 0\} \tag{2}$$

λ plays the role of a nonnegative vector in $\mathbb{R}^n$, moving on one can alter relation (2) into variable-returns-to-scale but by adding the constraint of λ (i.e., $\sum_{j=1}^{n} \lambda_j = 1$). The slacks for a DMU $(x_o, y_o) = (x_o^R, x_o^{NR}, y_o^R, y_o^{NR}) \in P$, is illustrated in relations (3):

$$\begin{aligned} \sigma x_o^R &= X^R \lambda + s^{R-} \\ x_o^{NR} &= X^{NR} \lambda + s^{NR-} \\ \tau y_o^R &= Y^R \lambda - s^{R+} \\ y_o^{NR} &= Y^{NR} \lambda - s^{NR+} \end{aligned} \tag{3}$$

with $\sigma \leq 1$, $\tau \geq 1$,and $\lambda, s^{R-}, s^{NR-}, s^{R+}, s^{NR+} \geq 0$. Generally speaking, the slacks are the vectors $s^{R-} \in \mathbb{R}^{k1}$,$s^{NR-} \in \mathbb{R}^{k2}$, $s^{R+} \in \mathbb{R}^{\ell 1}$,and $s^{NR+} \in \mathbb{R}^{\ell 2}$, the first two depict input overflows, while the last two showcase the output shortages. Overall, when the result is the following $\sigma = 1, \tau = 1$, $\lambda_o \geq 1$, $\lambda_j = 0$ $(\forall j \neq 0)$ and with zero slacks, then our model reaches feasibility. Based on Cooper et al. (2007, p.108) an hybrid efficient index ρ might be produced via the relation (4):

$$\rho = \frac{1 - \frac{k_1}{k}(1-\sigma) - \frac{1}{k}\sum_{i=1}^{k_2} s_i^{NR-} / x_{io}^{NR}}{1 + \frac{\ell_1}{\ell}(\tau - 1) + \frac{1}{\ell}\sum_{r=1}^{\ell_2} s_r^{NR+} / y_{ro}^{NR}} \tag{4}$$

A $DMU_O(x_o, y_o)$ is deemed as hybrid efficient, when $\rho = 1$ if $\sigma = 1, \tau = 1, s^{NR-} = 0,$ $and\ s^{NR+} = 0$. Under the assumption that the 45 DMUs operate with k inputs and produce a desirable (Y^D) and an undesirable output (Y^{UD}) and with vectors $x \in \mathbb{R}^{k}, Y^D \in \mathbb{R}^{\ell_1}, and\ Y^{UD} \in \mathbb{R}^{\ell_2}$, respectively. Moreover, the matrices are $X = [x_1, \ldots, x_n] \in \mathbb{R}^{k \times n}$, $Y^D = [y_i^D, \ldots, y_n^D] \in \mathbb{R}^{\ell_1 \times n}$ and $Y^{UD} = [y_i^{UD}, \ldots, y_n^{UD}] \in \mathbb{R}^{\ell_2 \times n}$, hence assuming that X, Y^D, and $Y^{UD} > 0$, then, the production possibility set takes the form as in relation (5):

$$P = \{(x, y^D, y^{UD}) |\ x \geq X\lambda, y^D \leq Y^D\lambda, y^{UD} \geq Y^{UD}\lambda, \lambda \geq 0\} \tag{5}$$

Where D shows the desirable and UD shows the undesirable outputs respectively. Though a $DMU_O(x_o, y_o^D, y_o^{UD})$ can be characterized as efficient even if it incorporates undesirable outputs, only if there is not any vector $(x, y^D, y^{UD}) \in P$ with at least one strict inequality and $x_o \geq x,\ y_o^D \leq y^D,\ y_o^{UD} \geq y^{UD}$. The expressions (6) and (7) shows such an example:

$$\rho^* = min \frac{1 - \frac{1}{k}\sum_{i=1}^{k} \frac{s_i^-}{x_{io}}}{1 + \frac{1}{\ell_1 + \ell_2}\left(\sum_{k=1}^{\ell_1} \frac{s_K^D}{y_{k_o}^D} + \sum_{k=1}^{\ell_2} \frac{s_K^{UD}}{y_{k_o}^{UD}}\right)} \tag{6}$$

Subject to

$$\begin{aligned} x_o &= X\lambda + s^- \\ y_o^D &= Y^D\lambda - s^D \\ y_o^{UD} &= Y^{UD}\lambda + s^{UD} \\ s^- &\geq 0,\ s^D \geq 0,\ s^{UD} \geq 0, \lambda \geq 0 \end{aligned} \tag{7}$$

In expressions (6) and (7) one can interpret that the vectors exhibit overflows in inputs (i.e., $s^- \in \mathbb{R}^{k}$) and the undesirable output (i.e., $s^{UD} \in \mathbb{R}^{\ell_2}$), on the contrary there are shortages in the desirable output (i.e., $s^D \in \mathbb{R}^{\ell_1}$).

In eco-efficiency performance it is adequate to state the impact of separability. Halkos & Polemis (2018) observed the influence of separability as carbon pollutants treated as undesirable output were not separable from the other desirable outputs, leading to the conclusion that a rise in undesirable output ushers to an increase of the desirable output and contrariwise. Furthermore, there is also debate about inseparability for the variables of mathematical modelling. In such case one can split outputs (Y^D, Y^{UD}) into separable desirable (Y^{S_D}), non-separable desirable (Y^{NS_D}), and non-separable undesirable $(Y^{NS_{UD}})$ outputs. Similarly, inputs can be separated into separable $(X^S, where\ X^S \in \mathbb{R}^{k_1 \times n})$ and non-separable $(X^{NS}, where\ X^{NS} \in \mathbb{R}^{k_2 \times n})$. The production form for the separable desirable outputs is the same as in relation (2), but the production form for the non-separable outputs is expressed in relation (8):

$$P_{NS} = \{(X^S, X^{NS}, Y^{S_D}, Y^{NS_D}, Y^{NS_{UD}}) | x^S \geq X^S\lambda, x^{NS} \geq X^{NS}\lambda, y^{S_D} \leq Y^{S_D}\lambda, y^{NS_D} \leq Y^{NS_D}\lambda, y^{NS_{UD}} \geq Y^{NS_{UD}}\lambda, \lambda \geq 0\} \tag{8}$$

A $DMU_O\left(x_o^S, x_o^{NS}, y_o^{S_D}, y_o^{NS_D}, y_o^{NS_{UD}}\right)$ is deemed as non-separable efficient if for any $\psi(0 \leq \psi \leq 1)$ $\left(x_o^S, x_o^{NS}, y_o^{S_D}, \psi y_o^{NS_D}, \psi y_o^{NS_{UD}}\right) \notin P_{NS}$ and together with at least one strict inequality, i.e. $x_o^S \geq x^S$, $x_o^{NS} \geq x^{NS}$, $y_o^{S_D} \leq y^{S_D}$, $y_o^{NS_D} = y^{NS_D}$, $y_o^{NS_{UD}} = y^{NS_{UD}}$. Therefore, the hybrid model takes the below form:

$$\rho^* = min \frac{1 - \frac{1}{k}\sum_{i=1}^{k_1}\frac{s_i^{S-}}{x_{io}} - \frac{k_2}{k}(1-\psi)}{1 + \frac{1}{\ell}\left(\sum_{k=1}^{\ell_1}\frac{s_r^{S_D}}{y_{k_o}^{S_D}} + (\ell_1 + \ell_2)(1-\psi)\right)} \tag{9}$$

Subject to

$$\begin{aligned} X_O^S &= X_S\lambda + s^{S-} \\ \psi X_O^{NS} &= X_{NS}\lambda \\ Y_O^{S_D} &= Y_{S_D}\lambda + s^{S_D} \\ \psi Y_O^{NS_D} &\leq Y^{NS_D}\lambda \end{aligned} \tag{10}$$

$$\psi Y_O^{NS_{UD}} \leq Y^{NS_{UD}}\lambda$$

$$s^{S-} \geq 0, s^{S_D} \geq 0, \lambda \geq 0, 0 \leq \psi \leq 1$$

3.2. Mathematical modelling of Window DEA

In the influential publication by Charnes et al. (1984) it has been recommended the WDEA modelling by adopting the moving average method, allowing for comparison between DMUs but also with itself too. Therefore, WDEA technique goes beyond the juxtaposition between N DMUs (n=1,…,N) with $\mathscr{k}$ inputs and ℓ outputs during a period t (t=1,…,T). The input and output matrices are expressed as:

$$x_n^t = \begin{bmatrix} x_n^{1t} \\ \vdots \\ x_n^{\mathscr{k}t} \end{bmatrix} \quad y_n^t = \begin{bmatrix} y_n^{1t} \\ \vdots \\ y_n^{\ell t} \end{bmatrix} \tag{11}$$

Furthermore, under the assumption that a window begins in a period v $(1 \leq v \leq T)$ and with window width w $(1 \leq w \leq T - v)$, the form of the above matrices becomes:

$$x_{vw} = \begin{bmatrix} x_1^v & x_2^v & \cdots & x_N^v \\ x_1^{v+1} & x_2^{v+1} & \cdots & x_N^{v+1} \\ \vdots & \vdots & \ddots & \vdots \\ x_1^{v+w} & x_2^{v+w} & \cdots & x_N^{v+w} \end{bmatrix}$$

$$y_{vw} = \begin{bmatrix} y_1^v & y_2^v & \cdots & y_N^v \\ y_1^{v+1} & y_2^{v+1} & \cdots & y_N^{v+1} \\ \vdots & \vdots & \ddots & \vdots \\ y_1^{v+w} & y_2^{v+w} & \cdots & y_N^{v+w} \end{bmatrix} \tag{12}$$

It is widely known that in order to calculate eco-efficiency, one should use a ratio of desirable output to undesirable output. As a result, the higher the value of this ratio gets, the greater the eco-efficiency of the DMU. To exemplify, in our research we calculate the eco-efficiency performance, of the most GHGs polluting– developed and developing – countries $(N = 45)$ due to electricity utilization that operate with $\mathscr{k}$ $(\mathscr{k} = 3)$ inputs in order to produce ℓ $(\ell = 3)$ outputs.

$$f_m = \sum_{i=1}^{\ell} p_{im} y_{im} \Bigg/ \sum_{j=1}^{k} q_{jm} x_{jm} \qquad (13)$$

Where p_{im} and q_{jm} denote the output and input weights respectively. It ought to be noted that eq. 13 considers some constraints:

Subject to

$$\sum_{i=1}^{\ell} p_{im} y_{im} \Bigg/ \sum_{j=1}^{k} q_{jm} x_{jm} \leq 1 \; for \; m = 1, \ldots, N$$

$$and \qquad (14)$$

$$p_{im}, q_{jm} \geq 0$$

After all, our model utilizes windows with width 5, aiming to grasp the impact of meso-term green policies on DMUs' performance. Moreover, the present research observes the period 1995 – 2022 (t=28). Henceforth, there are 24 number of windows (nw=t–w+1), additionally, our analysis calculates the eco-efficiency performance of 5400 DMUs (DMUs=N*w*nw).

3.3. Mathematical modelling of club clustering

In our analysis we monitor eco-efficiency and then the club clustering in the period 1995 – 2022 during which several phenomena took place, inter alia the global financial crisis of 2008, COVID-19, and the Russo-Ukraine War followed by the energy crisis in commodity prices. An original technique has been proposed by Phillips and Sul (2007), namely the "log t" regression test that is an extension of club convergence through non-linear time-varying factor model. Additionally, log t regression utilizes an interesting algorithm that does grouping based on the variables' common characteristics (Du, 2017). This is the reason why we have selected to utilize the log t regression on the eco-efficiency results from hybrid WDEA, essentially through this modelling we use a flexible panel data analysis that takes into account eco-efficiency and decompose it into two elements as below:

$$Eff_{it} = g_{it} + a_{it} = \left(\frac{g_{it} + a_{it}}{u_t}\right) u_t = \delta_{it} u_t \tag{15}$$

where

- Eff_{it} represents eco-efficiency performance respecting their efforts to green transition for a DMU i *(i= 1,…, 45)* at time t (*t*= 1995,…, 2022).
- g_{it} represents the systematic common components and a_{it} embodies transitory components.
- u_t denotes a single common component and δ_{it} is a time varying idiosyncratic element which captures the idiosyncratic distance between the common factor u_t and the systematic part of Eff_{it}.

The time-varying term δ_{it} as in a semi-parametric structure as follows:

$$\delta_{it} = \delta_i + \frac{\sigma_i \xi_{it}}{L(t) t^{\alpha}} \tag{16}$$

where

- δ_i and a scale parameter σ_i are fixed, across the panels
- ξ_{it} is an i.i.d random variable with mean equal to zero and variance equal to unity across i, but weakly dependent over t
- $L(t)$ is a slowly varying function, an example of the function $L(t)$ is $log(t)$, which becomes infinite as t approaches infinity and;
- α captures the decay rate of cross-sectional variations, that is the rate of convergence of Eff_{it} toward δ_i.

In this circumstance, Phillips and Sul (2007) developed a regression t test for the null hypothesis of convergence. The null hypothesis and its alternative (i.e., divergence) are then obtained as

$$H_0: \delta_{it} = \delta \; and \; a \geq 0 \; against$$
$$H_1: \delta_{it} \neq \delta \; and \; a < 0 \tag{17}$$

In order to test and regarding the transition parameter δ_{it} Phillips and Sul (2007) used the following relative transition paths:

$$h_{it} = \frac{Eff_{it}}{N^{-1}\sum_{i=1}^{N} Eff_{it}} = \frac{\delta_{it}}{N^{-1}\sum_{i=1}^{N} \delta_{it}} \quad (18)$$

h_{it} denotes transition path associated with the behaviour of individual i with respect to the cross-section mean at time t.

Supposing, that h_{it} converges to unity, for all $i = 1, 2, \ldots, N$, with $t \rightarrow \infty$, or if $\delta_{it} \rightarrow \delta$ as $t \rightarrow \infty$, there is a convergence process. Therefore, the convergence hypothesis defined in eq. 18 can be obtained as in eq. 19, which describes that the cross-sectional variation converges to zero.

$$H_{it} = \frac{1}{N}\sum_{i=1}^{N}(h_{it} - 1)^2 \rightarrow 0 \quad (19)$$

Then, the so-called ''log t'' regression model can be used through the following equation:

$$\log\left(\frac{H_1}{H_t}\right) - 2logL(t) = a + \beta \log(t) + \varepsilon_t \quad (20)$$

where

- $\frac{H_1}{H_t}$ is a cross-sectional variance ratio
- $t = [\varphi T], [\varphi T]+1, \ldots, 5 > 0$
- φT is the initial observation in the regression with $\varphi > 0$. Based on Monte Carlo experiments, the setting $\varphi = 0.3$ is suggested for a short period, i.e., when $T \leq 50$ (Phillips & Sul, 2007).
- $L(t) = \log(t)$
- α is a parameter indicating the rate of convergence, and β is the regression parameter

By adopting this methodology, a one-sided t-test for heteroskedasticity and autocorrelation is applied to the β-coefficient. Therefore, the null-hypothesis of convergence can be rejected if the t-statistic of the test does not exceed −1.65 as a critical value at a 5% significance level. Phillips and Sul (2007) coined a method that takes into consideration both convergent and divergent clubs as follows in Figure 2.

Figure 2: The log t methodology. Figure created by the authors based on the methodology of Phillips and Sul (2007).

Step 1

Sorting of the countries in a descending order. This sorting is applied based on the last observation in the time series dimension of the panel.

Step 2

Creation of a fundamental set. The size is decided based on the log-t regression until the $t_{\hat{\beta}}$ for that group exceeds -1.65. If not, there is no convergence.

Step 3

After the creation of the initial set, the log-t regression assesses each country according to the condition of convergence ($t_{\hat{\beta}} > -1.65$).

Step 4

Repeat the process in order to create other convergence clubs. If the null hypothesis is rejected, then Steps 1-3 are repeated to decide if this set can be divided into other groups. If Step's 2 condition is not met, then the rest countries present divergence.

Step 5

Application of the merging test for each pair of the initial clusters. If there is convergence, then the clubs can be merged into broader clusters. Lastly, there is repeat of the process till there is no other convergence option.

Step 6

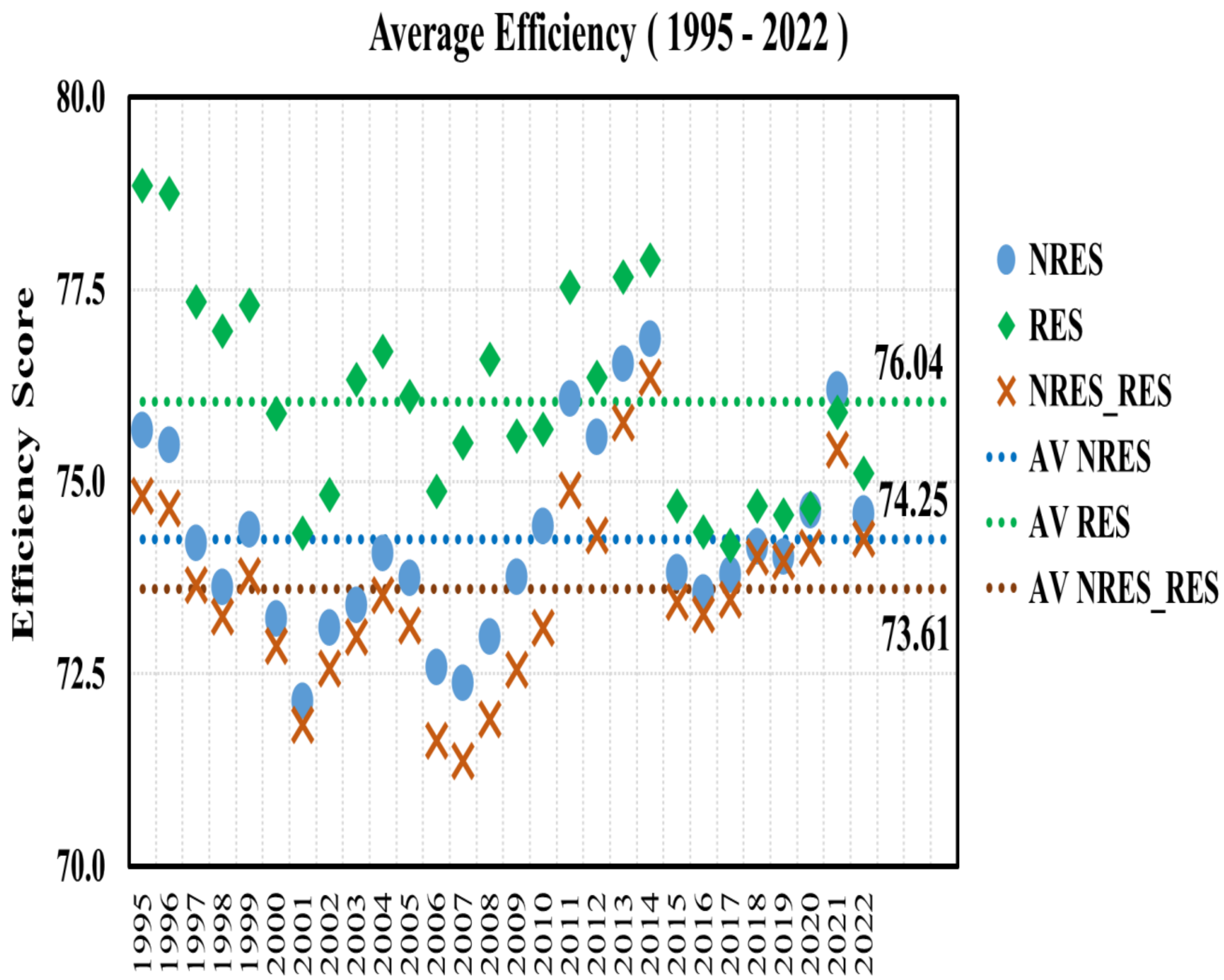
Interpretation of the results regarding the speed of convergence.

Convergence Status	$\hat{\beta}$	$t_{\hat{\beta}}$
Absolute Convergence	> 2	> -1.65
Conditional Convergence	$0 \leq \hat{\beta} < 2$	> -1.65
The weakest convergence clubs	< 0	> -1.65

4. Results and Discussion

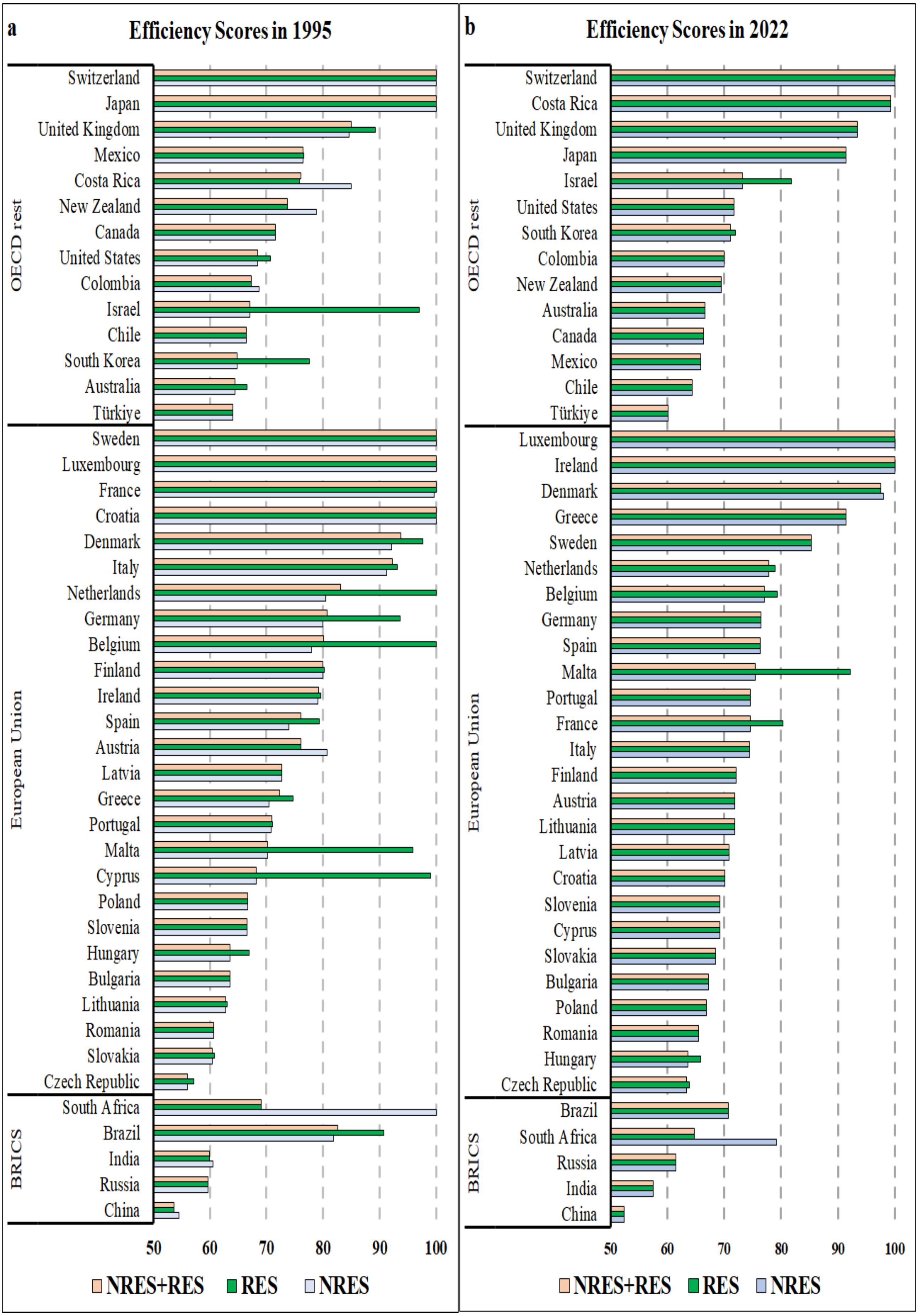
The results presented at Figure 3 show the average national eco-efficiency performance based on our hybrid WDEA model with width 5 of the 45 DMUs spanning the years 1995 – 2022. The first research question about the difference between the eco-efficiency pathways of the 45 most emitting counties indeed is ratified by the results. The impact of RES has excessively positive impact on eco-efficiency, this is shown by the average eco-efficiency of the model which is 76% (green dotted line) contrary to the NRES model and NRES_RES model that have 74% (blue dotted line) and 73% (brown dotted line) respectively. More specifically, in supplementary material exist the exact eco-efficiency scores for all models at Supplementary Material (Tables S.1 – S.9).

Figure 3: Average efficiency in the period 1995 - 2022



Having these in mind, it is also interesting to inspect what happens regarding the different economies as categorized in EU, OECD rest countries, and BRICS. In Appendix C there are the annual average eco-efficiency of the three economic coalitions. For the NRES model (Figure C.1), the EU's eco-efficiency aligned with the OECD performance after the years 2014, on the contrary, the BRICS's performance was de-aligned after 2006. The RES (Figure C.2) and NRES_RES (Figure C.3) models exhibit similar results on average performances, especially for the BRICS misaligned eco-efficiency pathway after 2005 that falls down to 65% or lower performance. These specific outcomes showcase the separation of economic growth between, firstly in the EU and OECD, and secondly in the BRICS. Leading to the conclusion that energy sectors in BRICS ought to consider more financial and technological instruments towards the green transition pathways as they need groundbreaking solutions in order to re-align their eco-efficiency performance.

Figure 4: Efficiency scores for the three models in the years 1995 (a) and 2022 (b)



The difference in eco-efficiency scores in the years 1995 and 2022 is illustrated at Figure 4. In 1995 the hybrid efficient countries in NRES in the EU are Croatia, Luxembourg, and Sweden, in OECD are Japan and Switzerland, and for BRICS only South Africa. In addition for the NRES_RES model are the same countries, but with the addition of France for the EU. Moving on to the RES model, we have the same results with the addition of Netherlands and Belgium in the EU. On the other hand, there relatively fewer hybrid efficient countries in the year 2022, for all models, in the EU only Ireland and Luxembourg are efficient, whereas for the OECD only Switzerland, nevertheless there is no efficient country for the BRICS economies. It should be also noted that for both years and all models China, Russia, and India belong to the countries with the lowest eco-efficiency performance with values that range between 50% and 62%. Keeping in mind the possible differences in eco-efficiency performance it might be easier to compare the countries performance based on the hierarchy.

The top-tier performances in hierarchical categorization, as illustrated in Table 3, are Luxembourg, Japan, United Kingdom, Switzerland, and Sweden, however the lower eco-efficiencies are in Türkiye, Romania, Czech Republic, Russia, India, and China. In the difference between the NRES_RES to RES nine countries are stable, twenty-five are downgraded, and eleven are upscaled. For instance, Costa Rica lost eight places followed by Italy, Brazil, and Austria that declined by five slots, whereas the greatest gains are in Cyprus (7 places), South Korea (9 places), Malta (10 places), and specifically Israel to have won 18 slots.

Table 3: Hierarchical categorization of average efficiency in ascending order based on RES model. Note: the green arrow (↑) shows that the country has greater efficiency by adopting the RES, the yellow arrow (→) illustrates stability, whereas the red arrow (↓) depicts lower average efficiency.

Countries	NRES_RES	NRES	RES	Change from NRES_RES to RES	Change from NRES to RES
Luxembourg	1	1	1	→	→
Japan	2	2	2	→	→
United Kingdom	5	6	3	↑	↑
Switzerland	3	3	4	↓	↓
Malta	15	15	5	↑	↑
Sweden	4	5	6	↓	↓
Israel	25	25	7	↑	↑
Denmark	6	7	8	↓	↓
France	8	10	9	↓	↑
Ireland	10	14	10	→	↑
Netherlands	14	16	11	↑	↑
Italy	7	9	12	↓	↓
Cyprus	20	22	13	↑	↑
Belgium	16	18	14	↑	↑
Greece	11	11	15	↓	↓
Germany	12	12	16	↓	↓
Costa Rica	9	4	17	↓	↓
Brazil	13	13	18	↓	↓
Spain	19	21	19	→	↑
South Korea	29	29	20	↑	↑
Portugal	18	20	21	↓	↓
Austria	17	17	22	↓	↓
Finland	21	23	23	↓	→
Colombia	22	19	24	↓	↓
South Africa	23	8	25	↓	↓
New Zealand	24	24	26	↓	↓
United States	26	26	27	↓	↓
Lithuania	28	28	28	→	→
Croatia	27	27	29	↓	↓
Hungary	35	35	30	↑	↑
Mexico	30	31	31	↓	→
Australia	36	36	32	↑	↑
Slovenia	31	30	33	↓	↓
Latvia	32	32	34	↓	↓
Canada	33	33	35	↓	↓
Chile	34	34	36	↓	↓
Slovakia	39	39	37	↑	↑
Bulgaria	37	37	38	↓	↓
Poland	38	38	39	↓	↓
Türkiye	40	40	40	→	→
Romania	41	41	41	→	→
Czech Republic	43	43	42	↑	↑
Russia	42	42	43	↓	↓
India	44	44	44	→	→
China	45	45	45	→	→

Moreover, regarding the juxtaposition between the NRES and RES models there are twenty-two countries that are losing their place, but fourteen are getting better. For example, South Africa lost 17 places followed by Costa Rica with 13 slots, by contrast again Cyprus and South Korea gained 9 places, Malta 10 slots, and Israel 18 places. To recapitulate, Israel eco-efficiency efforts are the most fruitful regarding the amelioration of overall performance, adversely Costa Rica has the greatest losses in terms of hierarchical performance. Till now the main eco-efficiency results have been presented, but we propose the application of club convergence in order to monitor the occurrence of convergence and observe which DMUs are making efforts to catch-up with the most advanced, green-oriented, economies.

We examine, first, whether the convergence hypothesis is ratified for the entire sample. Next in order, we investigate the potential outcome of convergence of the clubs using the clustering algorithm proposed by Phillips and Sul (2007). Moreover, we apply the log t regression for the convergence test. As an outcome we take the coefficient, standard error, and t-statistic for log(t). One can interpret that when t-statistic (calculated as –95.281, –96.252 and –119.890 in NRES, RES and NRES_RES, respectively) is less than -1.65, therefore the null hypothesis (i.e., convergence) is rejected at the 5% level (Table 4).

Table 4: The log t test regression results for the entire sample

	NRES	RES	NRE_SRES
$\hat{\beta}$	–0.787	–0.683	–0.913
$St\ Err_{\hat{\beta}}$	0.008	0.007	0.008
$t_{\hat{\beta}}$	–95.281	–96.252	–119.890

Following the above results, the null hypothesis is rejected in all three cases (NRES, RES and NRES_RES). Therefore, we now employ the clustering algorithm to classify minor groups converging their steady states in NRES, RES and NRES_RES since the convergence of all groups is rejected (Table 5).

Table 5: Identification of convergence Clubs

Initial Classification	Club members
NRES	
Club 1 (12)	Costa Rica, Denmark, Greece, Ireland, Israel, Japan, Luxembourg, Malta, Spain, Sweden, Switzerland, United Kingdom
Club 2 (7)	France, Germany, Italy, Lithuania, Netherlands, Portugal, South Africa
Club 3 (17)	Australia, Austria, Belgium, Brazil, Colombia, Croatia, Cyprus, Czech Republic, Finland, South Korea, Latvia, New Zealand, Poland, Romania, Slovakia, Slovenia, United States
Club 4 (3)	Bulgaria, Canada, Mexico
Club 5 (2)	Chile, Hungary
Club 6 (3)	India, Russia, Türkiye
Not convergent Group 7 (1)	China
RES	
Club 1 (14)	Costa Rica, Denmark, France, Greece, Ireland, Israel, Italy, Japan, Luxembourg, Malta, Portugal, Sweden, Switzerland, United Kingdom
Club 2 (31)	Australia, Austria, Belgium, Brazil, Bulgaria, Canada, Chile, China, Colombia, Croatia, Cyprus, Czech Republic, Finland, Germany, Hungary, India, South Korea, Latvia, Lithuania, Mexico, Netherlands, New Zealand, Poland, Romania, Russia, Slovakia, Slovenia, South Africa, Spain, Türkiye, United States
NRES_RES	
Club 1 (12)	Costa Rica, Denmark, Greece, Ireland, Japan, Luxembourg, Malta, Portugal, Spain, Sweden, Switzerland, United Kingdom
Club 2 (30)	Australia, Austria, Belgium, Brazil, Bulgaria, Canada, Chile, Colombia, Croatia, Cyprus, Czech Republic, Finland, France, Germany, Hungary, India, Israel, Italy, South Korea, Latvia, Lithuania, Mexico, Netherlands, New Zealand, Poland, Romania, Russia, Slovakia, Slovenia, United States
Club 3 (3)	China, South Africa, Türkiye

From the initial classification, in Table 5, it can be concluded that there are six clubs and one non convergent group for the NRES model, two clubs for RES, and three clubs for NRES_RES. Next in order, it is examined in Table 6 the possibility of merging between the aforementioned clubs. In general, the club convergence algorithm shows two things: if there is convergence and the categorization of clubs from greater to lower eco-efficiency scores. For example, in the NRES model the greatest convergence speed is in club 4 that has average efficiency of 66.2%, in the same way can the results be interpreted for the rest results.

Table 6: Club convergence results and a possible club merging

NRES						
	Club1	**Club2**	**Club3**	**Club4**	**Club5**	**Club6**
$\hat{\beta}$	0.053	1.914	0.751	4.340	–0.767	0.659
$t_{\hat{\beta}}$	2.284	32.322	8.477	3.163	–0.377	3.897
Av. Efficiency (%)	86.466	79.387	69.330	66.286	65.451	60.796
	Club1+2	**Club2+3**	**Club3+4**	**Club4+5**	**Club5+6**	**Club6+ Group7**
$\hat{\beta}$	–0.533	0.788	0.543	3.379	–0.617	–0.249
$St\ Err_{\hat{\beta}}$	0.054	0.085	0.093	1.296	0.098	0.096
$t_{\hat{\beta}}$	–9.940	9.243	5.818	2.607	–6.311	–2.594
RES						
	Club1	**Club2**				
$\hat{\beta}$	–0.250	0.074				
$t_{\hat{\beta}}$	–1.506	1.347				
Av. Efficiency (%)	89.695	69.876				
	Club1+2					
$\hat{\beta}$	–0.683					
$St\ Err_{\hat{\beta}}$	0.007					
$t_{\hat{\beta}}$	–96.252					
NRES_RES						
	Club1	**Club2**	**Club3**			
$\hat{\beta}$	0.262	0.038	0.884			
$t_{\hat{\beta}}$	3.658	0.758	11.349			
Av. Efficiency (%)	86.008	69.755	62.501			
	Club1+2	**Club2+3**				
$\hat{\beta}$	–0.842	–0.236				
$St\ Err_{\hat{\beta}}$	0.011	0.029				
$t_{\hat{\beta}}$	–74.918	–8.054				

Table 7: Final club classifications

Final Club classifications	**Club members**
NRES	
Club 1 (12)	Costa Rica, Denmark, Greece, Ireland, Israel, Japan, Luxembourg, Malta, Spain, Sweden, Switzerland, United Kingdom
Club 2 (32)	Australia, Austria, Belgium, Brazil, Bulgaria, Canada, Chile, Colombia, Croatia, Cyprus, Czech Republic, Finland, France, Germany, Hungary, India, Italy, Korea Rep., Latvia, Lithuania, Mexico, Netherlands, New Zealand, Poland, Portugal, Romania, Russia, Slovakia, Slovenia, South Africa, Türkiye, United States
Not convergent Group 3 (1)	China
RES	No clubs can be merged
NRES_RES	No clubs can be merged

The final club classification is presented at Table 7 and shows that in NRES model there are two clubs with twelve and thirty-two countries respectively, along with one non-convergent club that includes only China. The average eco-efficiency scores in Table 8 for NRES clubs 1 and 2 are 86.4% and 70.3% respectively. Furthermore, the algorithm does not provide any further merging either for RES or NRES_RES models, meaning that the initial classifications are the final as well.

Table 8: Final attributes of the NRES model club convergence

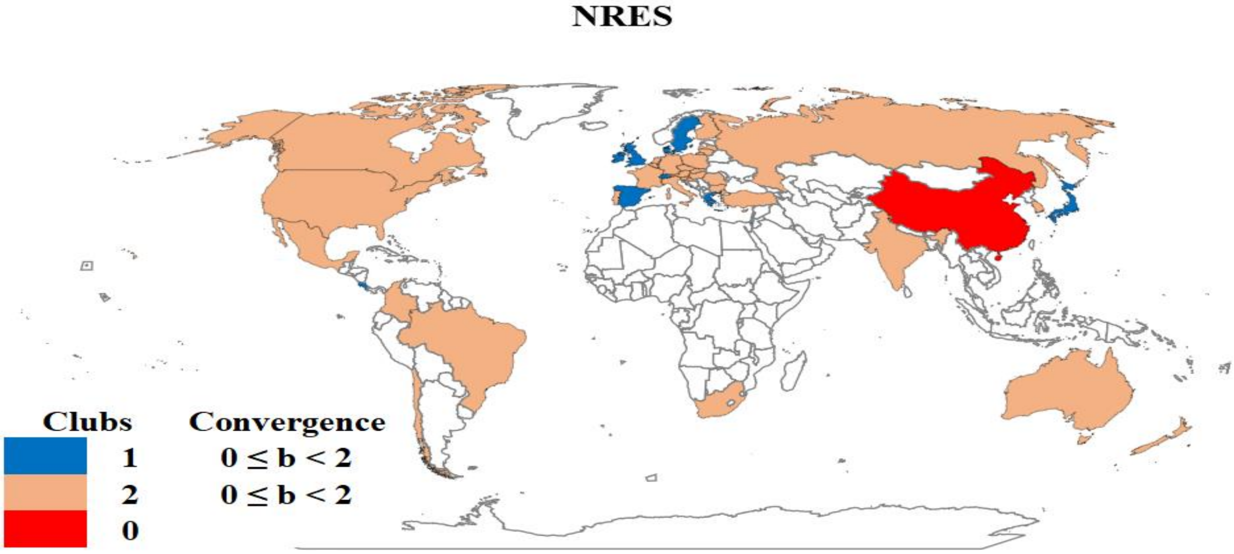
	Club1	**Club2**
$\hat{\beta}$	0.053	0.090
$t_{\hat{\beta}}$	2.284	1.573
Av. Eco-efficiency (%)	86.466	70.332

A summary of the club converge clubs is illustrated in Map 1. Map 1a shows the existence of two final clubs with conditional convergence and one non convergent group in NRES model, moreover club 1 has 86.4% eco-efficiency is composed of twelve countries none of which are in BRICS and club 2 has 70.3% eco-efficiency and includes thirty-two DMUs with all BRICS except China that belongs to the non-convergent group.

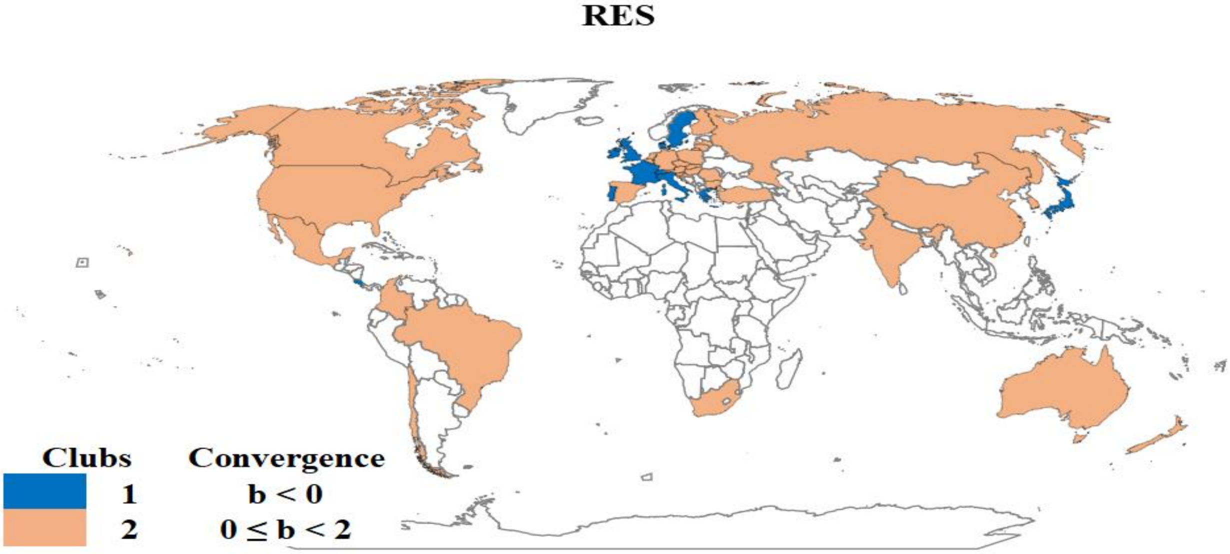
Furthermore, Map 1b presents the outcome for RES model that has two clubs. RES club 1 has slower speed of convergence than club 2, even though club 1 has greater efficiency with (89.6%) against club 2 (69.8%). The RES convergence club 2 contains all BRICS countries, even though they present conditional convergence.

Lastly, in NRES_RES model and in Map 1c there is conditional convergence on all three clubs, but club 1 has average 86% eco-efficiency, followed by club 2 with 69.7% and club 3 with 62.5%. Interestingly, South Africa, China, and Türkiye belong to the third convergent group with the lowest eco-efficiency as stated before, showing again that BRICS ought to accelerate and strengthen their efforts towards sustainable development and green transition race.

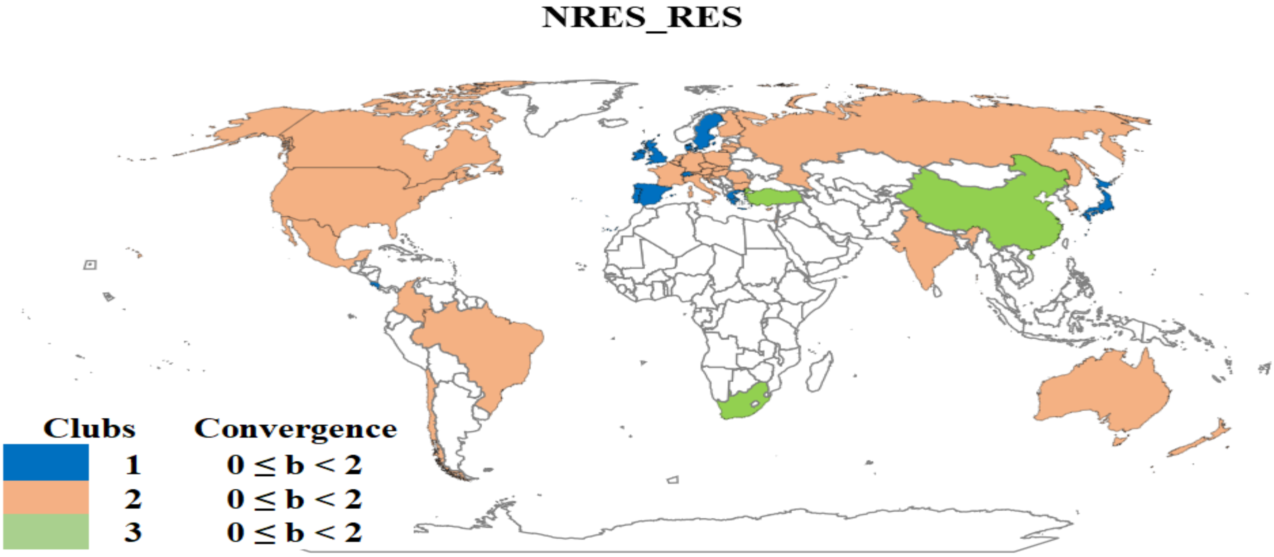
Map 1: Club convergence results



(a)



(b)



(c)

Important is also to mention that in Appendix D there are the specific clubs and average eco-efficiency performances for each year in the period 1995 – 2022. In Figure D.1 (i.e., NRES model) the club 1 range is between 81% and 93%, club 2 range is from 68% to 72% significantly lower than club 1, and the non-convergent group is China with values between 50% and 56%. Club 1 is composed mainly by European countries either from EU (i.e., Denmark, Greece, Ireland, Luxembourg, Malta, Sweden, and Spain), or from the UK and Switzerland, showing a potential path for European integration. Additionally club 1 includes Japan, Costa Rica, and Israel.

Moving on Figure D.2 (i.e., RES model), club 1 range is between 84% and 94% similar to NRES club 1 values, whereas club 2 has excessively lower performance range between 67% and 73%. Again club 1 is composed primarily of European countries as France, Portugal, and Italy have been added to this specific club, on the other hand Spain now belongs to club 2. Leading to the conclusion that the RES model showcases a greater integration among European countries regarding green transition.

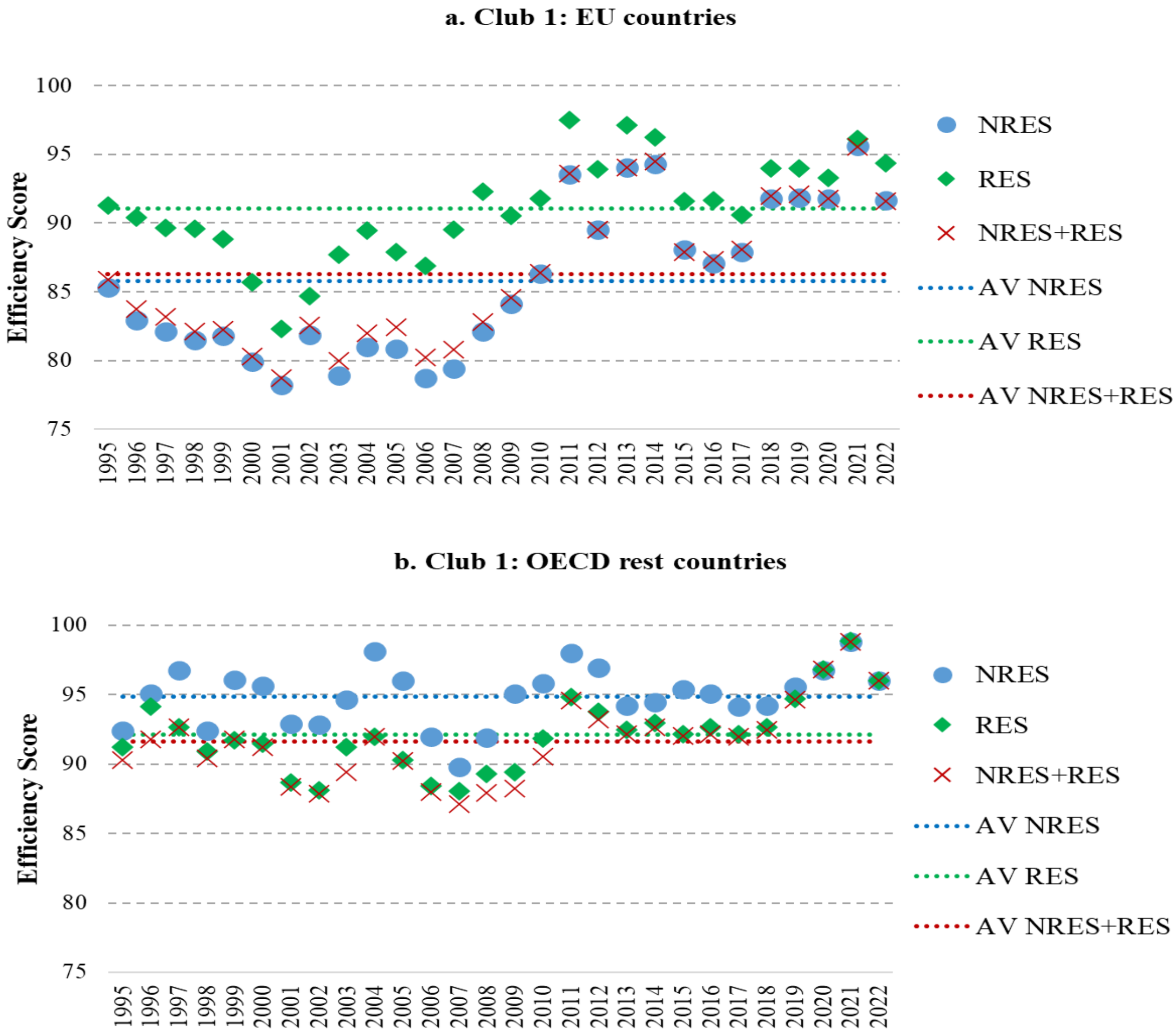
Accordingly, in Figure D.3 (i.e., NRES_RES model), club 1 has values (80 – 93%) like the previous models, club 2 eco-efficiency range is from 68% to 71% which shows the lowest variation in all three models, and club 3 that ranges between 58% and 73% that illustrates the highest variation among the models. Meaning that in NRES_RES the convergence of Türkiye and South Africa with the performance of Chine lead to greater fluctuations. Important is to delve into the most convergent club, i.e. club 1, which is similar to the NRES model with the exception of Portugal that now belongs to this group, whereas Israel has been transferred to club 2.

In order to perform a comparative analysis of the OECD and EU countries as well as the group of emerging BRICS countries, the common countries of Clubs 1 and 2 are then determined for each of the three efficiency indicators NRES, RES and NRES_RES.

The countries that belong to Club 1 for all three efficiency indicators are divided into EU countries (Denmark, Greece, Ireland, Luxembourg, Malta and Sweden) and OECD countries (Costa Rica, Japan, Switzerland and the United Kingdom) (Figure 5). Accordingly, the countries that belong to Club 2 for all three efficiency indicators are divided into the EU countries (Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Finland, Germany, Hungary, Latvia, Lithuania, the Netherlands, Poland, Romania, Slovakia and Slovenia), the OECD countries (Australia, Canada, Chile, Colombia, the Republic of Korea, Mexico, New Zealand and the United States) and the BRICS countries (Brazil, India and Russia) (Figure 6).

In the case of Club 1, the countries with the highest efficiency scores for all three indicators (NRES, RES and NRES_RES) are included. Regarding the degree of convergence, the countries show the weakest convergence for the efficiency index RES and a conditional convergence for the other two efficiency indices NRES and NRES_RES.

Figure 5: Average efficiencies in club 1. (a) in EU and (b) OECD rest.



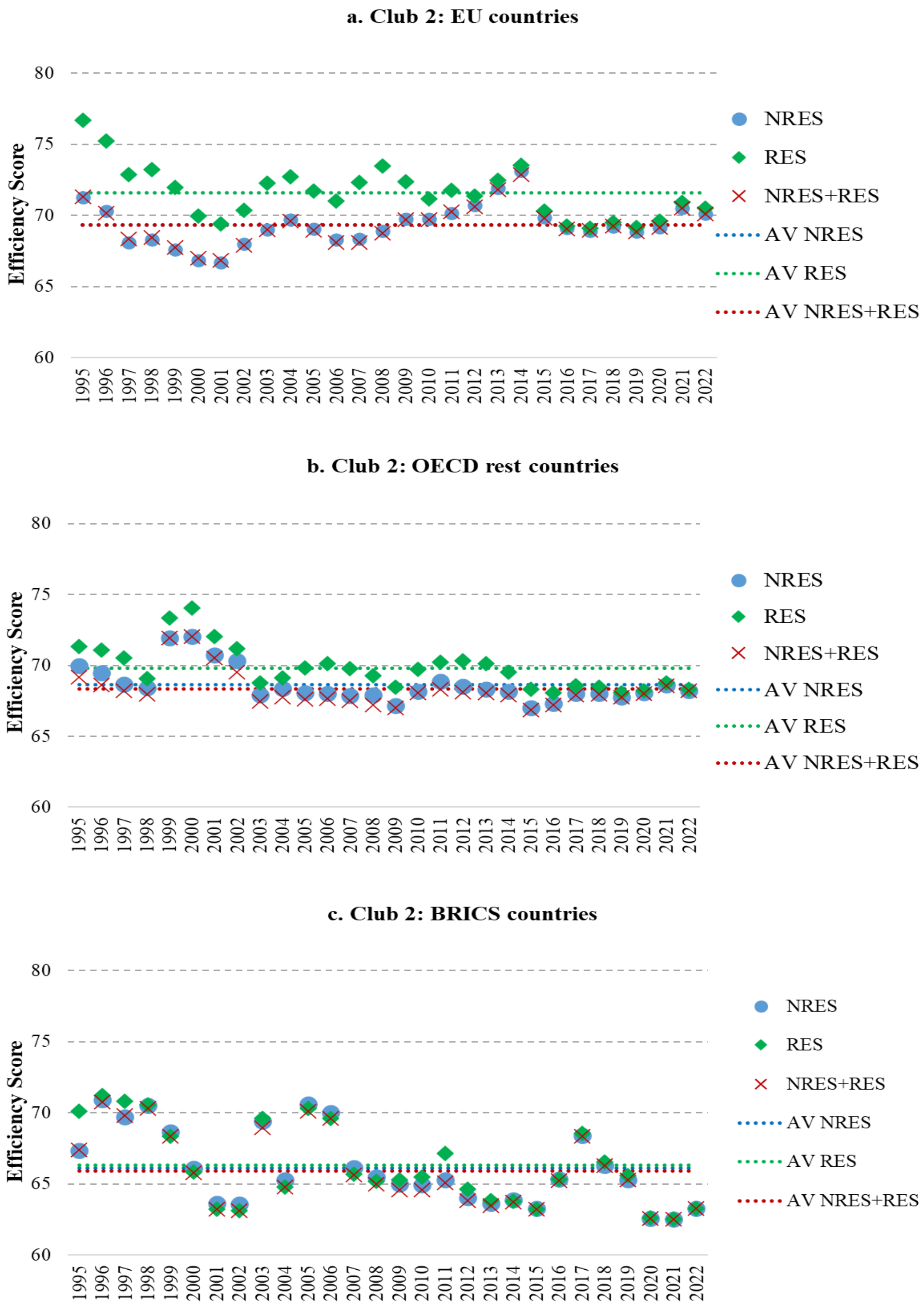
It is worth noting that in the case of the EU countries, the RES index performs better than the other two efficiency indices (Figure 5a). In contrast to the EU countries, the NRES index in the OECD countries performs better than the other two indices (Figure 5b). This fact shows that the countries concerned need to implement a targeted action plan aimed at using existing know-how and developing modern technologies and best practices in the field of energy modernization, the circular economy, and the adoption of clean energy sources.

The countries in Club 2 show a conditional convergence and have a lower efficiency level compared to the countries in Club 1 for all three indicators (NRES, RES and NRES_RES). The RES index exceeds the other two efficiency indices both in the case of the EU countries and in the case of the OECD countries (Figures 6a and 6b). This indicates that ensuring energy efficiency promotes the consumption of renewable energy sources in the long term.

However, the highest values of the RES indicator with the greatest deviation from the other two indices can be observed for the EU countries. For the OECD countries under consideration, it is considered necessary to further increase investment in the development of renewable energy technologies in order to secure energy efficiency in the long term. These countries are below the threshold for energy production from renewable sources compared to the EU countries (Figures 6a and 6b).

The BRICS countries of Club 2, which are characterized by high rates of development and industrialization, show similar efficiency scores for all three indicators over time (Figure 6c). This fact could be linked to these countries' heavy dependence on fossil fuels, which is hampering the energy transition and thus the long-term goal of carbon neutrality by 2050.

Figure 6: Average efficiencies in club 2. (a) in EU, (b) OECD rest, and (c) BRICS.



Our empirical analysis shows that the EU is ahead of the OECD and the BRICS countries in the green transition race, with the latter having the lowest level of ecological efficiency. As far as we are aware, there are only two studies in the international literature that approximate the methodological approach used in this article. The specific studies use the parametric Malmquist index approach and the non-parametric Malmquist-Luenberger productivity index in combination with the log t algorithm to investigate the convergence trend of productivity indicators. More specifically, Bai et al. (2019) observed total factor carbon productivity in 88 countries over the period 1975–2013, but with the SFA method. Additionally, a log t algorithm was used to monitor the extent to which there is convergence in terms of carbon efficiency. In their results, there was no convergent trend, meaning that five clubs were constructed with fluctuation in terms of productivity performance, furthermore higher investments in GDP per capita and research and development were linked to greater performance.

Sun et al. (2020) combined Malmquist DEA results with a log t regression and examined environmental productivity in a panel of 104 countries from 1980 to 2016. An interesting technique is that they have observed club convergence not on the whole period but in every decade, however this can lead to different pathways. Club convergence can provide crystal clear direction when applied to the entire period. Therefore, in the present study, we focused on the convergence trend of eco-efficiency indicators for the whole period. Sun et al. (2020) concluded that the structure of industrial sectors, energy prices and market openness may be significant factors in environmental performance. In addition, developed countries showed higher convergence than developing countries, which may not be comparable to our results as we focused on the countries with the highest GHG emissions. The relevance to our research is that we agree regarding their statement about the proper implementation of environmental efficiency policies that should consider both global and regional needs and opportunities as noted before regarding the divergence between OECD and EU in comparison with the BRICS economies.

5. Conclusions and policy implications

The first important result of our empirical analysis shows the positive impact of RES on the eco-efficiency of the forty-five countries, which was taken into account through the construction of three DEA eco-efficiency models (first research question). This finding was the starting point for further deepening and understanding the transition pathways of the clubs (second and third research questions). To this end, we conducted a comparative analysis between the EU, OECD and BRICS country groups, which allowed us to examine the research findings from the first (eco-efficiency) and second (convergence of clubs) stage of our analysis simultaneously (i.e., Figures 5 and 6).

This highlights best practices for the green transition and provides policy makers with guidance on how to accelerate the dynamic convergence towards eco-efficiency. Accordingly, the highest average eco-efficiency performance can be attributed to Luxembourg, Japan, United Kingdom, Switzerland, and Sweden, whereas the lower eco-efficiencies are in Türkiye, Romania, Czech Republic, Russia, India, and China.

Conditional convergence can be observed for all clubs in all three efficiency indices, with the exception of Club 1, which shows the weakest convergence in the RES efficiency index. Conditional convergence shows that countries with similar steady states show convergence but do not converge to the same steady state. Despite the specificities of the energy transition in each country, which may be related to factors such as international climate commitments, high RES costs and the increase in carbon emissions, harmonization of national and international energy standards is crucial.

With this in mind, we identified countries' eco-efficiency indicators and investigated the extent to which they converge. In particular, eco-efficiency indicators have been used to quantify the countries' need for a new energy mix based mainly on RES while limiting carbon dioxide (CO_2) and methane (CH_4) emissions. In this way, using the club cluster technique, we were able to examine both the degree of convergence and the potential for alignment of clean energy transition policies in the EU, OECD and BRICS sample countries.

As the analysis shows, the EU's energy profile is characterized by a tendency to move away from the consumption of fossil fuels and towards the increased use of RES. The observed transformation of the EU's energy system through a significant increase in the share of RES has been facilitated by the increasing competitiveness and lowering of electricity generation costs for green technologies.

The structural change in the European Union's electricity mix caused by Russia's invasion of Ukraine in 2022. The gradual decline in Russian oil and gas imports has reinforced the EU's efforts to move further away from fossil fuels and marks the entry into a new era of green energy transition and stronger energy security. In contrast to the EU, the picture is very different for the OECD and BRICS countries. As our empirical analysis shows, they are lagging behind the EU in the race for the green transition, as the largest share of total electricity still comes from fossil fuels. Furthermore, the analysis shows that the BRICS countries have the lowest level of eco-efficiency compared to the other two groups of countries (EU, OECD). This fact is a consequence of the increasing demand for electricity due to intensive urbanization and industrialization.

It would be interesting to extend the present study to the economic sectors of the countries studied, such as construction and manufacturing. The limitation in this case lies in the countries with incomplete data at sector level. The empirical analysis could also be directed towards a detailed examination of the factors contributing to the convergence or divergence of efficiency levels of the EU, OECD and BRICS countries.

To recapitulate, green energy transition is at risk as multi-crisis escalates. Geopolitical conflicts, e.g., the Russo-Ukrainian conflict, destabilized global economy. For instance, the EU developed a series of strategies such as the REPowerEU Plan, aiming to become more energy-independent from Russian fossil fuels and turning to domestic renewables. For the transition to green energy in EITE sectors, it is important to strengthen the factors that contribute to the convergence of eco-efficiency and to increasing the share of RES in final energy consumption. In a nutshell, the forty-five studied countries have due to their EITE sectors and have paved the way through NDCs in line with Net Zero goal and Paris Agreement on climate change (e.g., SDG7), in short this can be achieved through cooperation agreements that promote knowledge exchange and technology transfer with regard to the transition to green energy.

Appendix A

Table A.1: Recent publications in efficiency performance of energy sectors.

DMUs (Period)	**Techniques**	**Inputs**	**Outputs**	**Highest Effciencies**	**Reference**
29 Chinese regions (2000 – 2008)	DEA window	(1) Capital Stock in billion RMB. (2) Labor in million workers. (3) Energy in million tons of coal equivalent (Mtce).	(1) Desirable: GDP in RMB billion. (2) Undesirable: CO_2 in million tons (Mt). (3) Undesirable: SO_2 in million tons (Mt).	East area of China	Wang et al. (2013)
20 OECD countries (1985 – 2011)	SBM-DEA and GLMM-MCMC	(1) Labor in number of employees. (2) Renewable and non-renewable energy consumption in thousand tons of oil equivalent. (3) Productive capital stock (in constant US dollars).	(1) Desirable: Income (GDP) in constant US dollars. (2) Undesirable: CO_2 emissions in thousands of metric tons of carbon).	European Union	Apergis et al. (2015)
OECD & BRICS (1993-2010)	SBM-DEA, window analysis, and Tobit model	(1) Workforce. (2) GFCF. (3) Energy Consumption.	(1) Desirable: GDP. (2) Undesirable: CO_2 emissions.	France, Italy, Canada, UK USA,	Camioto et al. (2016)
BRICS	SBM-DEA and window analysis	(1) GFCF. (2) Energy. Consumption.	(1) Desirable: GDP. (2) Undesirable: CO_2 emissions.	Brazil, South Africa	Camioto et al. (2015)
26 OECD & China (2000 – 2010)	Dynamic DEA	(1) Land area. (2) Population. (3) Energy Use (4) Carry-over: Energy Stock.	(1) Desirable: GDP (2) Undesirable: CO_2 emissions.	Belgium, Denmark, Ireland, Israel, Japan, Netherlands, Switzerland, UK, and USA	Guo et al. (2017)
26 European countries	Output-oriented (CRS &	(1) Labor productivity. (2) Capital	(1) The ratio GDP per GHG.	United States and New Zealand	Moutinho et al. (2017)

(2001 – 2012)	VRS) DEA and Quantile Regression	productivity. (3) The weight of fossil energy. (4) Share of renewable energy in GDP.	emissions.		
27 OECD	Multiplicative Network DEA	(1) Capital (2) Labor (3) Land (4) Energy	(1) GDP (2) CO_2 emissions.	Switzerland, USA, and New Zealand	Ouyang and Yang (2020)
26 OECD (2013 – 2017)	Traditional DEA	(1) Population in millions (2) Primary Energy Consumption	(1) Desirable: GDP in buying power by means of billions of US$ in 2010 (2) Undesirable: CO_2 emissions in MT.	Brunei, Australia, Singapore, and Hong Kong	Iram et al. (2020)
G20 (G7, BRICS, and other G20) Economies (1996 - 2021)	Malmquist and Malmquist-Luenberger DEA-based	(1) Primary Energy Consumption MWH pc. (2) GFCF in million USD. (3) Labor in millions. (4) Political Stability & Absence of violence/terrorism as percentile. (5) Government effectiveness as percentile. (6) Rule of law as percentile.	(1) Desirable: GDP in current USD. (2) Undesirable: CO_2 emissions tons pc.	Indonesia, Mexico, Russia, China, India	Halkos & Aslanidis (2023)
EU-28 (1995 – 2019)	Static DEA and Dynamic DEA	(1) Labor force. (2) Capital stock. (3) Energy use. (4) Land use.	(1) Desirable: GDP in million USD. (2) Undesirable: CO_2 emissions. (3) Undesirable: CH_4 emissions.	Luxembourg, Sweden, Malta, Netherlands, and Denmark.	Halkos & Bampatsou (2022)

27 OECD (2000 – 2017)	SBM-DEA model and Malmquist-Luenberger Index	(1) Net capital stock. (2) Labor force (3) Energy. consumption.	(1) Desirable: GDP as desirable output. (2) Undesirable: Ecological footprint.	United Kingdom	Mamghaderi et al. (2023)
EU – 27 (1995 – 2019)	Malmquist and Malmquist-Luenberger DEA-based	(1) Electricity generation by RES GWh. (2) Electricity generation by NRES GWh. (3) Labor total. (4) GFCF in current USD.	(1) Desirable: GDP in current USD. (2) Undesirable: CO_2 emissions in kt. (3) Undesirable: CH_4 in kt of CO_2 equivalent.	Cyprus, UK, Netherlands France, Ireland, and Malta.	Halkos & Aslanidis (2024)

Appendix B

Table B.1: Characteristics of the DMUs, Data retrieved from the World bank and reference is the last available year.

Countries	Surface area (1000 sq. km)	Population (Million Persons)	Life Expectancy (years)	GDP Growth (annual %)
Australia	7741.22	26.01	83.30	4.27
Austria	83.88	9.04	81.24	4.81
Belgium	30.53	11.69	81.89	3.01
Brazil	8515.77	215.31	72.75	2.90
Bulgaria	111.00	6.47	71.51	3.93
Canada	15634.41	38.93	82.60	3.82
Chile	756.70	19.60	78.94	2.44
China	9562.91	1412.18	78.21	2.99
Colombia	1140.62	51.87	72.83	7.26
Costa Rica	51.10	5.18	77.02	4.55
Croatia	88.07	3.86	76.42	6.35
Cyprus	9.25	1.25	81.20	5.06
Czech Republic	78.87	10.67	77.37	2.35
Denmark	42.92	5.90	81.40	2.73
Finland	338.47	5.56	81.93	1.63
France	549.09	67.97	82.32	2.45
Germany	357.59	83.80	80.90	1.81
Greece	131.96	10.43	80.18	5.56
Hungary	93.03	9.64	74.47	4.55
India	3287.26	1417.17	67.24	7.24
Ireland	70.28	5.13	82.10	9.43
Israel	22.07	9.56	82.50	6.83
Italy	302.07	58.94	82.80	3.72
Japan	377.97	125.12	84.45	0.95
Latvia	64.59	1.88	73.28	3.36
Lithuania	65.29	2.83	74.34	2.44
Luxembourg	2.59	0.65	82.75	1.38
Malta	0.32	0.53	82.86	6.92
Mexico	1964.38	127.50	70.21	3.90
Netherlands	41.54	17.70	81.46	4.33
New Zealand	267.71	5.12	82.21	2.85
Poland	312.71	36.82	75.60	5.26
Portugal	92.23	10.41	81.07	6.83
Romania	238.40	19.05	72.96	4.60
Russia	17098.25	144.24	69.36	-2.07
Slovakia	49.03	5.43	74.71	1.75
Slovenia	20.48	2.11	80.88	2.46
South Africa	1219.09	59.89	62.34	1.91
South Korea	100.43	51.63	83.53	2.61
Spain	505.96	47.78	83.18	5.77
Sweden	528.86	10.49	83.16	2.91
Switzerland	41.29	8.78	83.85	2.57
Türkiye	785.35	84.98	76.03	5.53
United Kingdom	243.61	66.97	80.70	4.35
United States	9831.51	333.29	76.33	1.94
Average	**1841.13**	**103.32**	**78.36**	**3.83**

Appendix C

Figure C.1: Average efficiency scores for NRES model.

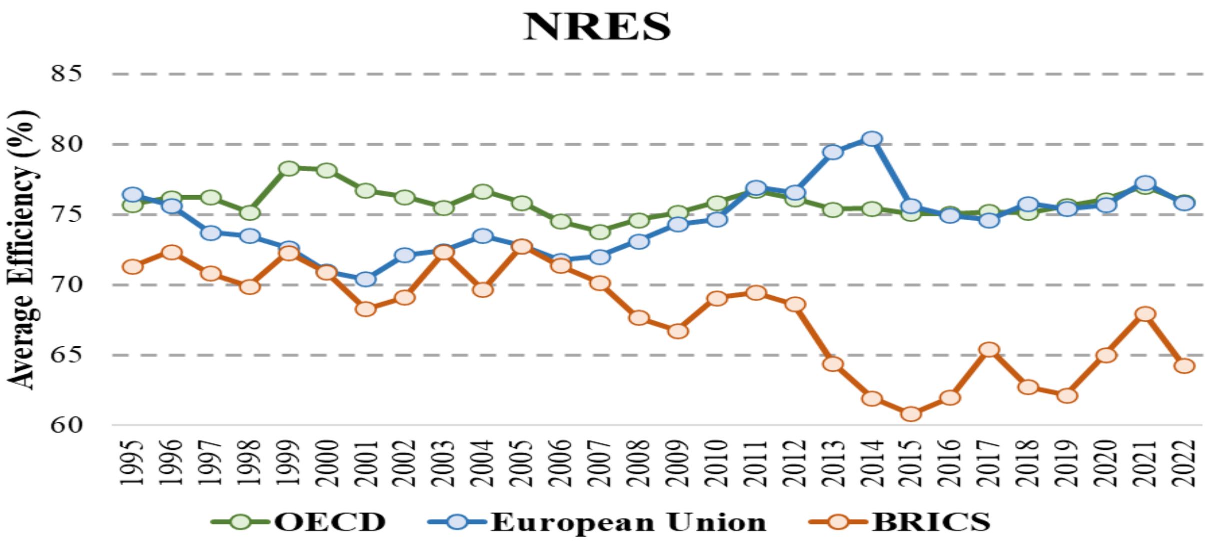


Figure C.2: Average efficiency scores for RES model.

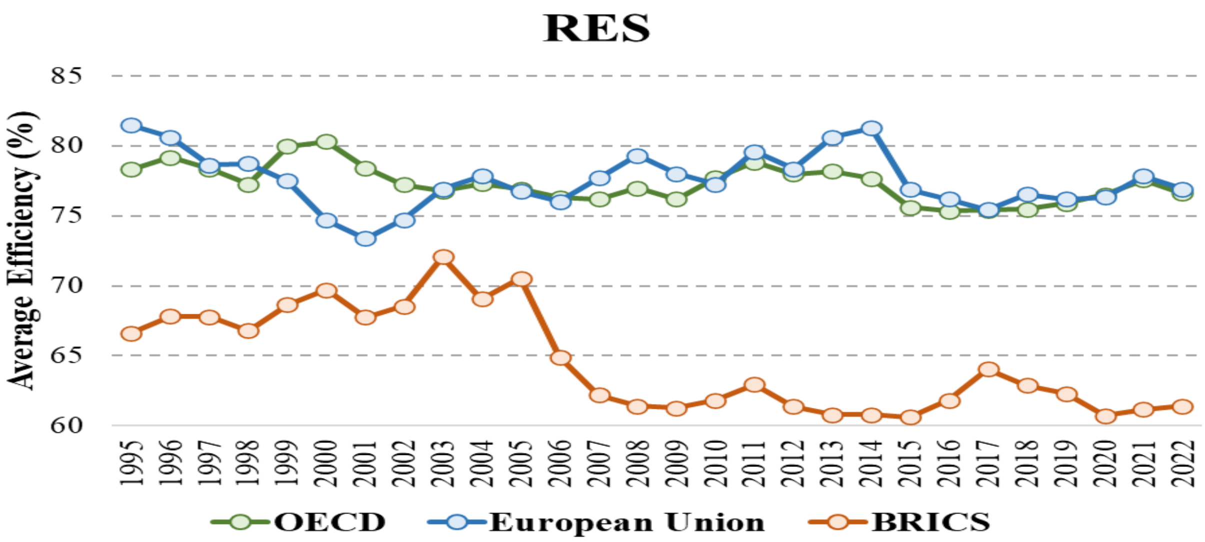
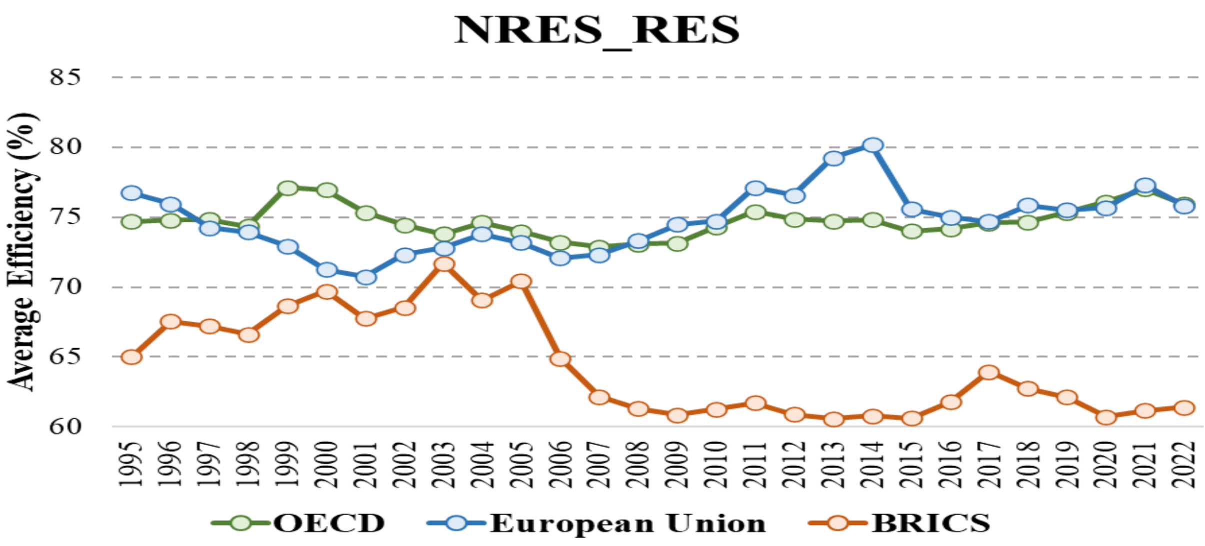


Figure C.3: Average efficiency scores for NRES_RES model.



Appendix D

Figure D.1: Clubs of average efficiency scores for NRES model.

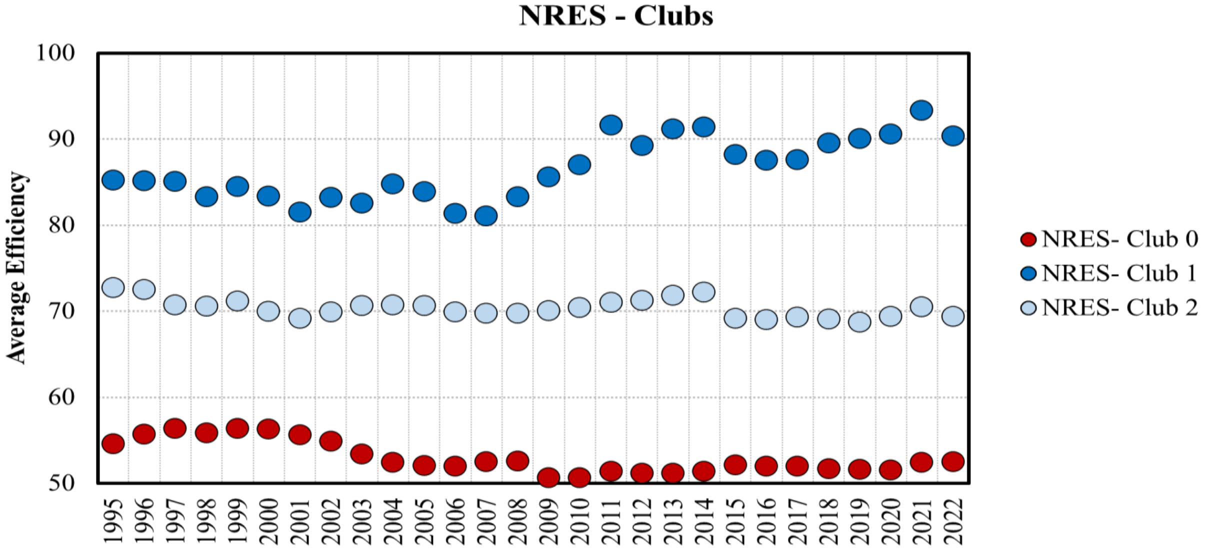


Figure D.2: Clubs of average efficiency scores for RES model.

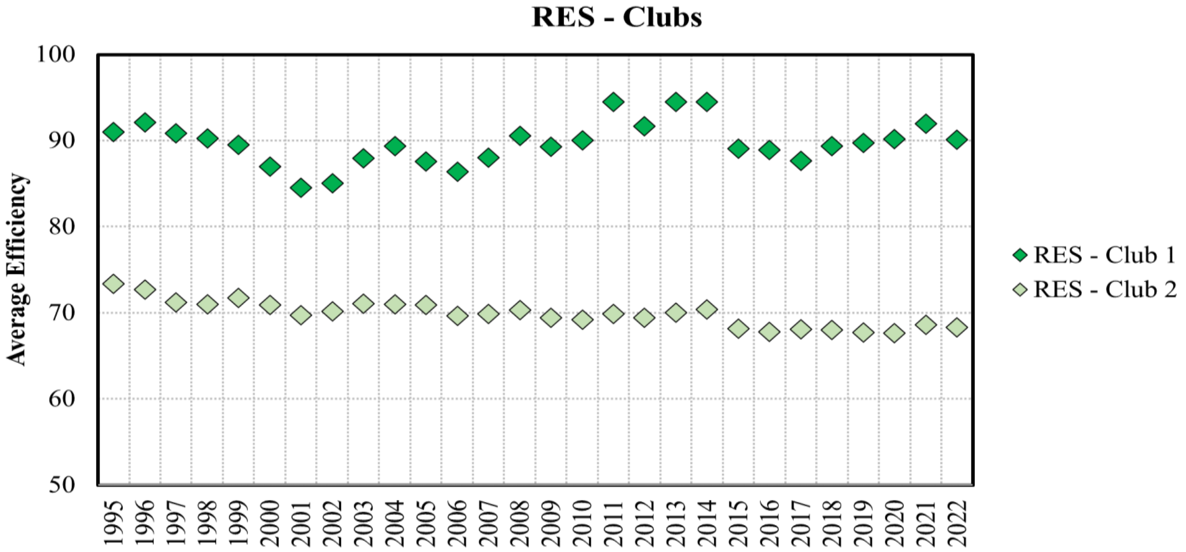
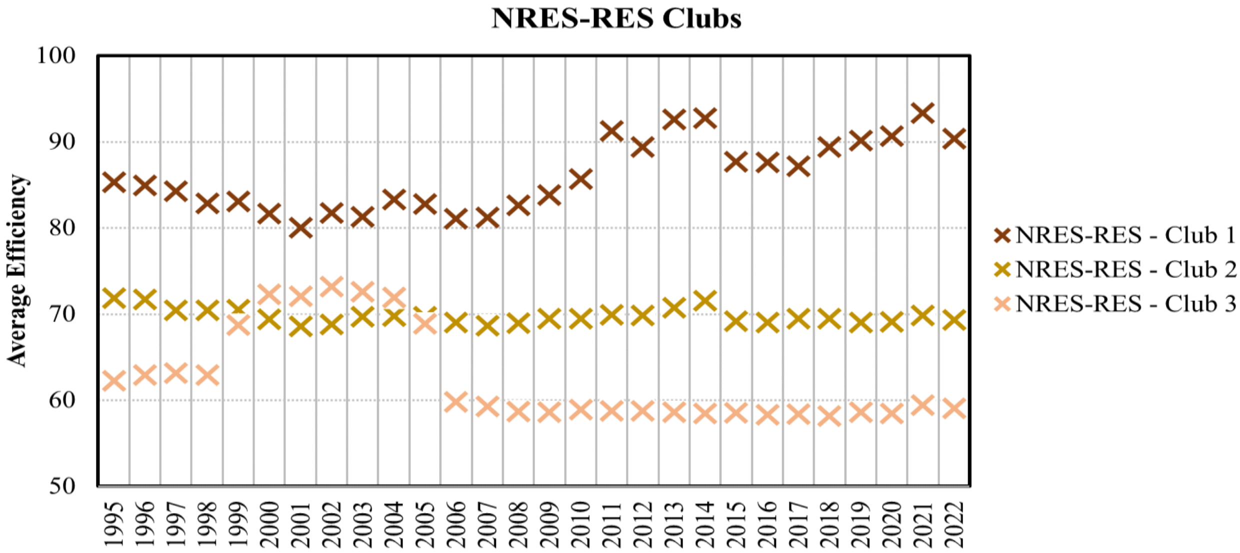


Figure D.3: Clubs of average efficiency scores for NRES_RES model.



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Supplementary Files

Table S.1. Efficiency scores (%) for NRES model (First 15 countries).

Years	Australia	Austria	Belgium	Brazil	Bulgaria	Canada	Chile	China	Colombia	Costa Rica	Croatia	Cyprus	Czech Republic	Denmark	Finland
1995	64.48	80.69	77.93	81.84	63.54	71.60	66.44	54.55	68.71	84.95	100.00	68.18	56.04	92.14	79.95
1996	65.28	75.68	77.26	91.24	100.00	70.20	65.27	55.66	71.52	100.00	77.56	69.00	56.29	82.10	73.57
1997	65.85	74.18	74.49	86.79	84.94	67.81	65.01	56.38	72.72	98.63	68.18	68.09	56.84	79.18	72.45
1998	64.64	76.93	75.61	88.43	71.41	67.42	65.13	55.81	72.89	83.66	68.62	76.89	58.10	80.19	73.17
1999	64.17	78.62	74.16	82.32	64.76	67.96	66.63	56.32	100.00	94.60	67.01	72.20	58.60	84.33	72.87
2000	63.95	74.10	71.79	76.62	63.58	68.82	67.33	56.28	100.00	100.00	67.44	72.65	57.83	81.05	71.06
2001	64.20	73.95	71.46	72.20	60.96	67.83	66.28	55.62	91.40	97.48	66.28	75.61	58.07	78.81	70.51
2002	63.49	78.48	75.92	70.62	61.44	67.52	65.68	54.87	87.19	98.41	65.26	70.00	59.26	80.85	72.18
2003	63.08	77.06	78.65	88.14	61.15	67.70	65.49	53.42	73.12	96.65	64.45	72.09	59.71	80.01	72.69
2004	63.73	81.25	77.27	76.25	60.93	67.65	66.71	52.44	74.66	100.00	65.31	72.38	60.57	87.64	73.46
2005	63.88	80.36	75.51	92.33	58.58	67.26	66.25	52.07	73.76	97.60	65.28	70.53	61.00	90.39	73.85
2006	63.54	82.72	75.06	91.12	57.91	66.95	69.79	52.00	71.27	90.50	64.94	68.16	61.32	75.93	72.08
2007	63.70	84.12	75.07	80.51	57.95	66.38	67.84	52.51	70.75	81.15	64.90	68.57	61.29	78.69	72.25
2008	64.07	82.74	74.47	78.90	57.23	66.41	64.36	52.59	77.69	85.64	65.11	68.67	62.40	83.16	73.27
2009	63.03	82.31	74.38	79.00	59.77	66.06	64.99	50.63	69.48	100.00	65.50	68.89	62.11	87.84	72.76
2010	63.95	78.58	73.84	77.29	61.59	65.75	66.21	50.65	71.70	100.00	67.98	69.08	61.94	92.15	71.38
2011	65.17	78.07	74.41	78.24	62.10	65.81	65.28	51.36	75.88	93.03	69.28	74.05	62.30	98.99	72.89
2012	65.33	77.28	73.54	74.43	62.01	65.43	64.70	51.14	76.53	93.68	69.67	83.14	62.09	96.68	71.73
2013	65.44	78.23	75.13	72.53	62.71	65.43	64.73	51.12	72.39	87.93	70.03	93.33	62.58	94.69	73.31
2014	65.37	83.02	75.12	73.32	62.38	65.14	65.09	51.35	70.29	87.43	70.77	97.48	62.61	100.00	74.94
2015	64.99	75.12	71.96	72.58	61.44	64.59	64.46	52.10	66.64	100.00	68.50	92.46	61.67	94.83	73.87
2016	64.53	74.38	72.01	79.44	63.18	65.04	64.90	51.99	66.98	98.10	68.07	69.18	62.28	88.25	71.57
2017	65.51	73.00	72.62	88.03	63.23	65.34	66.24	51.96	68.84	97.55	68.19	67.21	62.70	91.02	71.95
2018	65.56	73.35	72.94	82.25	63.70	65.40	66.09	51.71	69.04	93.40	68.93	69.50	62.85	89.74	71.35
2019	65.96	71.98	72.41	78.72	64.08	65.60	64.56	51.62	68.45	98.98	67.77	69.32	62.82	93.70	71.83
2020	66.01	71.49	75.68	70.85	64.48	65.26	65.25	51.56	68.65	100.00	66.75	67.62	63.07	93.08	72.74
2021	66.77	72.13	77.84	69.15	67.68	65.47	65.85	52.44	69.38	97.16	68.72	70.23	63.58	98.20	74.04
2022	66.65	71.90	77.05	70.78	67.20	66.37	64.41	52.47	70.00	99.24	70.12	69.18	63.33	97.97	72.12

Table S.2. Efficiency scores (%) for NRES model (Middle 15 countries).

Years	France	Germany	Greece	Hungary	India	Ireland	Israel	Italy	Japan	South Korea	Latvia	Lithuania	Luxembourg	Malta	Mexico
1995	99.67	80.03	70.43	63.62	60.61	79.07	67.12	91.29	100.00	64.80	72.68	62.82	100.00	70.23	76.43
1996	97.67	80.38	70.18	63.09	61.19	76.23	67.49	100.00	97.22	65.06	65.35	62.85	100.00	68.95	71.53
1997	95.64	79.06	70.65	63.15	60.81	74.86	68.16	97.89	92.80	64.71	66.19	62.86	96.41	71.71	70.38
1998	92.58	80.14	67.68	63.02	60.58	72.63	69.09	96.21	91.34	64.09	63.67	62.56	100.00	70.79	68.56
1999	88.50	78.71	66.86	62.51	59.77	71.06	69.01	90.96	96.93	65.62	64.63	64.13	100.00	73.17	70.31
2000	81.91	74.96	65.61	62.23	60.07	70.43	70.33	80.41	100.00	65.59	64.20	66.87	100.00	70.99	70.91
2001	80.41	77.08	65.75	62.79	58.37	70.20	69.90	79.93	95.92	65.05	63.16	65.46	95.76	73.41	73.43
2002	83.30	82.69	66.59	63.72	58.96	72.08	68.31	78.01	93.42	65.88	64.56	65.91	84.92	100.00	72.61
2003	86.14	86.55	66.90	64.56	59.17	72.87	69.50	82.27	95.87	66.18	64.71	66.45	88.35	71.71	68.94
2004	87.52	88.77	68.00	65.27	58.22	72.58	69.69	83.32	99.08	66.89	64.21	66.01	87.95	72.00	68.03
2005	84.90	85.61	70.83	65.50	57.43	71.72	68.72	79.58	97.28	68.28	63.90	65.75	87.73	69.03	68.29
2006	83.18	80.89	67.99	65.47	56.86	71.57	67.97	77.77	92.68	68.89	63.64	65.05	94.47	68.88	67.48
2007	83.28	82.57	67.11	66.21	56.44	72.80	67.65	78.50	89.87	69.31	65.67	65.20	95.47	68.84	66.65
2008	83.08	82.64	68.78	66.92	55.67	73.49	69.05	80.73	93.62	66.66	67.24	66.74	100.00	75.27	65.62
2009	83.85	82.40	71.34	66.05	55.63	79.36	69.64	82.75	94.94	64.89	69.44	73.40	96.66	77.40	64.47
2010	80.39	79.05	76.73	68.09	56.43	86.26	69.38	79.38	100.00	66.18	69.10	73.07	100.00	71.52	64.85
2011	80.28	79.48	90.30	68.99	55.56	98.80	68.41	81.60	100.00	66.91	66.51	72.50	100.00	77.47	64.41
2012	77.40	77.30	95.23	68.89	55.38	79.55	67.34	82.90	100.00	67.27	65.46	74.49	94.30	76.42	64.21
2013	79.25	78.23	97.81	67.82	56.00	85.20	68.97	89.54	92.28	68.56	66.73	74.07	100.00	86.40	65.37
2014	83.70	79.29	100.00	66.87	56.34	80.92	70.57	94.64	91.19	70.03	68.58	74.45	100.00	85.67	66.02
2015	80.18	75.59	98.59	65.62	56.88	75.94	71.29	83.19	89.13	69.95	67.78	70.25	94.96	72.95	64.45
2016	79.49	75.64	91.16	67.73	57.18	70.79	70.34	82.45	97.15	70.37	70.99	70.24	100.00	81.04	63.76
2017	78.35	75.97	87.82	65.65	57.36	72.79	71.91	82.05	97.00	71.36	70.29	70.91	97.51	88.96	64.30
2018	79.68	76.78	97.02	64.85	56.23	78.48	71.71	81.84	98.54	72.06	68.83	70.62	100.00	94.65	64.85
2019	78.13	76.40	100.00	63.91	56.90	79.96	72.86	80.25	99.68	71.32	68.98	69.80	93.46	90.24	65.61
2020	79.67	76.39	94.62	63.97	57.50	85.63	74.30	80.59	99.59	71.16	69.15	69.92	100.00	86.59	66.22
2021	78.03	77.65	93.30	64.11	57.18	99.32	74.36	78.32	100.00	72.71	70.12	70.99	100.00	90.02	66.25
2022	74.54	76.51	91.37	63.63	57.53	100.00	73.28	74.49	91.44	71.14	70.91	71.89	100.00	75.41	65.90

Table S.3. Efficiency scores (%) for NRES model (Last 15 countries).

Years	Netherlands	New Zealand	Poland	Portugal	Romania	Russia	Slovakia	Slovenia	South Africa	Spain	Sweden	Switzerland	Türkiye	United Kingdom	United States
1995	80.49	78.85	66.75	70.85	60.67	59.63	60.44	66.54	100.00	73.99	100.00	100.00	64.02	84.63	68.44
1996	76.62	78.40	63.76	71.19	59.70	60.29	57.88	65.76	93.56	76.65	100.00	100.00	63.40	83.13	68.56
1997	75.11	73.97	62.11	68.37	60.29	61.58	57.16	64.95	88.61	72.69	99.95	95.60	62.93	100.00	69.10
1998	76.33	75.33	61.88	67.93	62.60	62.48	57.13	65.13	82.28	72.01	97.65	96.73	66.44	97.83	69.47
1999	74.52	71.50	61.63	66.98	62.90	63.90	59.68	64.88	99.16	69.57	95.41	94.59	67.97	98.27	69.48
2000	73.00	70.36	61.93	66.23	62.07	61.57	61.49	64.16	100.00	67.51	91.57	90.69	65.75	91.94	69.34
2001	72.99	68.08	63.82	66.41	60.85	60.34	60.40	64.10	94.92	67.64	85.27	89.55	67.02	88.60	69.66
2002	76.71	69.79	65.15	66.77	60.85	61.07	61.28	65.04	100.00	67.59	86.87	90.63	66.17	88.81	70.35
2003	81.30	69.82	65.11	69.32	60.50	60.94	63.43	65.72	100.00	68.40	93.65	93.86	66.11	92.21	69.05
2004	83.29	70.83	65.00	69.88	61.64	61.40	64.35	65.75	100.00	68.75	97.72	93.35	64.74	100.00	68.38
2005	82.54	69.19	65.08	69.20	62.34	62.09	63.61	65.28	100.00	68.46	95.58	92.45	64.95	96.61	67.71
2006	80.78	68.83	64.29	70.87	61.60	62.01	64.22	64.86	94.88	68.46	93.44	90.51	63.69	94.11	67.52
2007	76.20	70.68	63.90	72.11	59.80	61.48	64.86	65.12	100.00	68.85	93.63	91.87	63.85	96.23	67.65
2008	79.87	70.26	64.38	72.27	59.98	61.91	65.45	65.22	89.37	70.10	91.88	93.92	64.51	94.50	68.48
2009	78.04	73.16	63.98	72.75	63.23	60.30	67.82	66.61	88.14	72.00	92.25	91.64	65.16	93.71	71.14
2010	79.58	75.69	64.86	73.85	63.07	61.01	66.85	68.38	100.00	73.36	91.41	91.78	64.32	91.56	70.87
2011	80.03	77.31	64.69	78.08	62.49	62.07	65.28	69.98	100.00	77.25	95.81	100.00	62.81	98.97	70.36
2012	81.36	74.86	64.84	84.17	62.10	62.30	67.72	69.93	100.00	78.21	94.82	96.70	63.07	97.34	69.84
2013	82.74	75.52	65.29	98.01	63.91	62.34	67.51	69.60	80.10	83.96	100.00	98.16	63.28	98.42	69.26
2014	85.60	74.81	64.88	95.66	64.30	61.92	68.29	71.55	66.79	82.33	99.21	100.00	62.60	99.24	68.62
2015	71.24	72.01	63.91	80.54	63.44	60.38	64.89	70.10	62.14	76.53	91.19	98.53	62.07	94.02	69.00
2016	74.15	73.81	64.31	81.42	64.57	59.29	66.48	70.85	61.99	77.34	91.16	96.80	61.84	88.26	69.31
2017	74.67	73.29	64.86	74.79	65.12	59.80	66.27	70.13	70.10	75.20	89.05	95.13	60.63	86.79	69.28
2018	75.68	72.26	64.61	75.74	66.69	60.39	67.05	69.96	63.14	75.05	90.94	95.77	59.67	89.08	68.92
2019	74.69	71.29	64.75	76.07	65.96	60.15	66.97	69.85	63.29	74.65	93.61	95.09	61.16	88.63	69.45
2020	75.15	72.21	65.09	75.24	65.84	59.43	68.55	70.78	85.82	74.91	90.95	95.72	59.60	91.65	69.61
2021	77.88	71.82	66.86	74.99	65.85	61.21	69.59	70.99	100.00	77.12	92.74	99.50	60.00	98.49	70.66
2022	77.82	69.44	66.91	74.64	65.52	61.48	68.49	69.29	79.19	76.31	85.33	100.00	60.08	93.36	71.73

Table S.4. Efficiency scores (%) for RES model (First 15 countries).

Years	Australia	Austria	Belgium	Brazil	Bulgaria	Canada	Chile	China	Colombia	Costa Rica	Croatia	Cyprus	Czech Republic	Denmark	Finland
1995	66.63	76.05	100.00	90.76	63.54	71.60	66.44	53.71	67.37	75.82	100.00	99.00	57.21	97.61	80.20
1996	67.67	73.93	100.00	92.97	100.00	70.20	65.27	54.59	68.53	85.81	73.07	94.01	57.76	90.74	74.84
1997	68.51	73.38	95.62	90.81	84.94	67.81	65.01	55.19	69.67	82.14	67.37	90.41	58.11	87.04	73.07
1998	66.91	74.34	95.11	89.33	77.97	67.42	65.13	54.45	71.02	75.51	67.91	97.67	59.58	87.27	73.72
1999	65.91	75.28	92.31	82.33	64.79	67.96	66.68	54.83	100.00	77.30	66.82	91.78	59.83	88.36	73.53
2000	65.92	72.35	83.70	76.71	63.58	68.82	67.34	54.75	100.00	81.74	66.97	87.99	58.48	83.69	71.24
2001	65.09	71.92	82.01	72.22	60.96	67.83	66.28	54.28	89.22	79.20	66.12	88.14	58.63	81.00	70.85
2002	64.29	73.00	85.32	70.62	61.44	67.52	65.68	53.38	81.12	78.53	65.29	85.02	59.87	81.67	72.62
2003	64.23	73.34	91.65	89.99	61.15	67.70	65.49	51.61	69.65	76.06	64.63	94.68	60.45	81.78	72.93
2004	65.75	75.07	93.66	76.25	60.93	67.65	66.71	50.91	70.48	75.43	65.27	96.37	61.26	87.22	73.55
2005	66.24	75.64	87.53	92.86	58.58	67.26	66.25	50.71	69.72	74.72	65.25	92.86	61.66	88.34	74.44
2006	65.96	76.60	84.75	91.12	57.91	66.95	69.78	50.91	68.34	74.55	64.95	89.96	62.17	80.70	72.10
2007	66.87	77.86	88.47	80.71	57.95	66.38	67.90	51.36	68.13	70.29	64.98	91.39	62.93	83.95	72.25
2008	70.37	77.90	89.30	79.46	57.23	66.41	64.36	51.32	71.67	69.49	65.11	90.67	66.36	90.83	73.27
2009	67.70	77.94	86.09	81.09	59.82	66.06	64.99	49.06	68.51	72.80	65.49	81.54	64.62	90.93	72.81
2010	70.30	76.52	81.24	79.97	61.59	65.75	66.42	49.29	70.61	78.84	67.95	75.61	63.79	92.30	71.38
2011	72.62	76.13	83.85	84.38	62.10	65.81	65.28	49.85	70.77	79.31	69.28	75.45	64.21	98.99	72.90
2012	74.34	74.39	79.02	76.78	62.01	65.43	64.70	50.21	73.11	79.49	69.67	83.14	63.22	96.89	71.73
2013	73.24	74.53	78.53	73.62	62.71	65.43	64.73	50.44	71.29	80.35	70.03	93.33	63.39	95.03	73.43
2014	70.89	76.18	79.73	73.44	62.38	65.14	65.09	50.94	69.05	80.24	70.77	97.48	63.38	100.00	75.52
2015	69.26	73.50	73.16	72.59	61.44	64.59	64.47	51.87	66.45	86.94	68.49	92.46	62.15	91.59	73.87
2016	66.11	73.45	72.27	79.70	63.18	65.04	64.91	51.90	66.79	86.08	68.07	69.18	62.63	86.57	71.57
2017	66.35	72.69	73.00	88.61	63.23	65.34	66.25	51.92	68.72	87.14	68.18	67.46	62.92	89.69	71.95
2018	66.14	73.25	74.28	83.03	63.70	65.40	66.12	51.71	69.02	86.43	68.93	69.50	62.99	89.36	71.35
2019	65.99	71.98	72.90	79.69	64.08	65.60	64.56	51.62	68.45	95.17	67.77	69.32	62.99	93.58	71.83
2020	66.01	71.49	78.35	70.88	64.48	65.26	65.25	51.56	68.65	100.00	66.75	67.62	63.31	92.90	72.74
2021	66.77	72.13	80.07	69.15	67.68	65.47	65.85	52.44	69.38	97.16	68.72	70.23	64.08	97.80	74.04
2022	66.65	71.90	79.27	70.78	67.20	66.37	64.41	52.47	70.00	99.24	70.12	69.18	63.93	97.48	72.12

Table S.5. Efficiency scores (%) for RES model (Middle 15 countries).

Years	France	Germany	Greece	Hungary	India	Ireland	Israel	Italy	Japan	South Korea	Latvia	Lithuania	Luxembourg	Malta	Mexico
1995	100.00	93.68	74.68	66.95	59.96	79.58	97.05	93.11	100.00	77.57	72.68	63.04	100.00	95.92	76.61
1996	100.00	92.06	74.36	66.23	60.42	80.27	99.65	100.00	97.22	80.24	65.16	63.08	100.00	96.84	71.53
1997	98.80	89.01	75.15	66.55	60.05	81.55	99.12	97.89	92.80	78.20	66.19	63.48	97.38	96.66	70.57
1998	97.42	89.36	71.80	67.38	59.95	80.62	99.03	97.66	91.34	68.00	63.38	63.14	100.00	100.00	69.30
1999	92.80	87.58	70.46	66.49	58.88	81.91	97.43	93.04	96.93	72.14	64.37	64.85	98.77	98.27	70.87
2000	86.64	80.95	68.38	65.97	59.21	79.45	100.00	84.11	100.00	76.07	64.00	67.25	94.74	96.61	71.85
2001	84.71	81.22	68.75	67.05	57.15	79.64	100.00	83.32	96.08	72.69	62.84	66.34	88.35	91.00	73.83
2002	87.77	84.31	69.61	70.93	57.65	82.28	93.01	81.61	93.74	75.60	64.24	66.90	87.73	100.00	73.07
2003	91.32	87.46	70.73	71.89	57.84	88.86	93.66	84.65	95.87	72.28	64.49	68.55	96.25	94.91	69.73
2004	93.65	89.03	72.57	69.09	56.76	92.98	96.22	84.78	98.97	73.17	63.88	68.56	89.60	96.70	68.87
2005	91.89	85.93	72.21	68.90	55.97	90.75	91.98	82.45	97.45	80.25	63.68	68.65	88.70	91.66	69.02
2006	91.14	81.89	71.61	68.91	55.63	90.60	89.84	81.42	92.68	82.54	63.63	69.81	94.65	90.45	68.48
2007	94.74	83.54	74.38	71.40	55.16	96.78	91.05	83.89	90.07	80.94	65.10	73.25	95.51	92.75	68.03
2008	97.81	83.84	75.86	72.82	54.63	95.03	100.00	85.28	94.18	74.47	67.05	77.41	100.00	100.00	66.88
2009	95.55	83.38	73.48	69.48	54.68	88.41	95.85	84.40	96.80	70.23	68.85	74.98	98.07	100.00	65.74
2010	89.24	79.81	76.73	69.92	55.69	90.44	97.92	80.87	100.00	72.27	69.10	73.09	100.00	99.87	65.82
2011	97.53	80.23	91.54	71.29	55.04	98.80	100.00	82.95	100.00	73.20	66.68	74.23	100.00	99.71	65.99
2012	86.26	77.53	100.00	70.70	54.80	85.25	90.68	83.22	100.00	73.68	65.46	74.38	96.07	90.55	66.24
2013	86.64	78.36	97.81	70.63	55.58	89.72	100.00	88.96	92.28	74.34	66.73	74.72	100.00	100.00	67.40
2014	91.83	79.33	100.00	69.73	56.00	87.11	96.42	92.16	92.45	76.14	68.62	75.18	100.00	91.20	67.16
2015	83.66	75.59	98.59	67.15	56.66	86.00	81.47	83.19	89.29	75.24	67.96	70.86	95.15	87.11	65.36
2016	82.28	75.64	91.16	68.13	57.05	82.28	77.71	82.45	98.00	74.62	70.99	70.78	100.00	98.93	64.23
2017	80.34	75.97	87.82	66.22	57.31	86.47	77.78	82.05	97.25	75.10	70.29	71.14	96.49	94.07	64.56
2018	81.10	76.78	97.02	66.11	56.23	90.71	78.28	81.84	98.90	75.26	68.85	70.89	100.00	95.93	64.94
2019	79.70	76.40	100.00	65.88	56.90	89.72	78.06	80.25	100.00	73.63	68.98	70.35	93.50	93.32	65.61
2020	80.73	76.39	94.64	65.58	57.50	91.71	78.37	80.59	100.00	72.78	69.15	69.97	100.00	89.64	66.22
2021	81.53	77.65	93.30	66.45	57.18	100.00	80.58	78.32	100.00	73.97	70.12	70.99	100.00	93.00	66.25
2022	80.34	76.51	91.37	65.85	57.53	100.00	81.84	74.49	91.44	72.01	70.91	71.89	100.00	92.11	65.90

Table S.6. Efficiency scores (%) for RES model (Last 15 countries).

Years	Netherlands	New Zealand	Poland	Portugal	Romania	Russia	Slovakia	Slovenia	South Africa	Spain	Sweden	Switzerland	Türkiye	United Kingdom	United States
1995	100.00	73.73	66.75	71.07	60.67	59.63	60.79	66.56	69.11	79.31	100.00	100.00	64.02	89.18	70.74
1996	95.46	74.72	64.15	71.25	59.70	60.29	58.77	65.76	70.79	78.71	100.00	100.00	63.40	93.48	70.71
1997	91.67	72.75	63.04	68.37	60.29	61.58	58.28	64.95	71.39	75.43	99.95	95.60	62.99	100.00	71.65
1998	92.92	72.65	63.14	68.10	62.60	62.48	58.38	65.13	67.80	74.90	97.65	96.73	66.54	100.00	72.31
1999	93.29	70.82	62.79	69.87	62.90	63.90	60.45	64.88	83.36	74.57	95.41	94.30	68.21	98.37	72.54
2000	86.16	69.61	62.93	66.59	62.07	61.57	61.94	64.20	96.35	70.74	91.33	90.69	66.18	93.39	72.64
2001	83.95	68.03	64.46	66.49	60.85	60.34	60.82	64.24	94.85	69.16	85.27	89.50	67.02	89.82	73.35
2002	84.18	69.09	65.21	68.06	60.85	61.07	61.60	65.32	100.00	71.49	86.87	90.63	66.19	89.54	73.21
2003	88.79	69.25	65.13	70.18	60.50	60.94	64.31	66.19	100.00	71.11	93.65	93.27	66.23	99.67	71.66
2004	89.01	69.72	65.02	71.70	61.64	61.40	65.29	65.90	100.00	73.50	97.74	93.35	65.15	100.00	70.76
2005	87.40	69.19	65.14	71.33	62.34	62.09	64.06	65.44	91.01	74.66	95.58	91.42	65.32	97.63	70.58
2006	88.31	68.63	64.43	71.91	61.67	62.01	64.52	64.89	64.83	73.98	93.44	90.52	63.94	95.93	70.35
2007	92.69	70.19	64.70	73.07	60.16	61.21	65.43	65.42	62.58	74.11	93.63	91.87	65.00	100.00	69.98
2008	96.27	70.07	66.45	73.37	60.46	61.46	66.60	65.22	60.27	75.99	91.88	93.92	66.14	99.64	70.03
2009	89.74	72.82	64.80	73.37	63.32	60.04	68.45	66.62	61.57	73.96	92.21	91.64	65.85	96.36	71.66
2010	84.78	75.61	65.20	73.84	63.16	60.84	67.35	68.59	63.26	74.91	91.41	91.78	64.47	96.86	71.23
2011	87.53	77.16	65.17	78.08	62.74	62.00	66.17	70.20	63.49	78.29	95.95	100.00	63.02	100.00	70.83
2012	84.83	74.54	65.06	84.16	62.50	62.25	68.32	69.93	62.88	78.26	94.82	96.05	63.33	99.55	70.78
2013	85.81	74.32	65.48	94.70	64.10	62.33	68.11	69.60	62.01	83.96	100.00	97.65	63.47	99.64	70.34
2014	88.05	72.77	65.21	92.73	64.34	61.84	68.83	71.55	61.79	82.33	99.21	100.00	63.12	99.24	69.89
2015	75.74	70.87	64.02	80.54	63.48	60.38	65.39	70.10	61.63	76.53	91.19	98.15	62.25	94.27	70.23
2016	75.62	72.67	64.31	81.42	64.58	59.20	66.75	70.85	61.29	77.34	91.16	97.87	61.98	88.71	70.17
2017	75.80	72.52	64.86	74.79	65.16	59.79	66.42	70.13	62.72	75.20	89.05	97.22	60.68	87.11	69.83
2018	77.17	71.94	64.61	75.74	66.69	60.39	67.07	69.96	63.09	75.05	90.94	96.27	59.67	89.08	69.11
2019	76.78	71.26	64.75	76.07	65.96	60.15	66.97	69.85	63.20	74.65	93.61	95.09	61.16	88.63	69.50
2020	77.56	72.06	65.09	75.24	65.84	59.43	68.55	70.78	64.29	74.91	90.95	95.72	59.60	91.65	69.61
2021	79.52	71.65	66.86	74.99	65.85	61.21	69.59	70.99	65.90	77.12	92.74	99.83	60.00	98.49	70.66
2022	78.97	69.44	66.91	74.64	65.52	61.48	68.49	69.29	64.76	76.31	85.33	100.00	60.08	93.36	71.73

Table S.7. Efficiency scores (%) for NRES_RES model (First 15 countries).

Years	Australia	Austria	Belgium	Brazil	Bulgaria	Canada	Chile	China	Colombia	Costa Rica	Croatia	Cyprus	Czech Republic	Denmark	Finland
1995	64.48	76.05	80.12	82.61	63.54	71.60	66.44	53.71	67.37	76.07	100.00	68.18	56.04	93.69	79.95
1996	65.28	73.93	78.77	91.60	100.00	70.20	65.27	54.59	68.53	85.81	73.07	69.00	56.29	84.59	73.57
1997	65.85	73.38	75.30	87.82	84.94	67.81	65.01	55.19	69.93	82.15	67.47	68.09	56.84	81.94	72.45
1998	64.64	74.47	76.56	88.44	71.41	67.42	65.13	54.45	71.02	75.61	68.08	76.89	58.10	82.44	73.25
1999	64.17	75.42	75.17	82.32	64.76	67.96	66.63	54.83	100.00	77.59	66.84	72.20	58.60	85.92	72.92
2000	63.95	72.35	72.34	76.62	63.58	68.82	67.34	54.75	100.00	81.97	67.00	72.65	57.83	82.47	71.06
2001	64.20	72.05	72.07	72.20	60.96	67.83	66.28	54.28	89.22	79.55	66.12	75.61	58.07	80.06	70.51
2002	63.49	74.11	76.13	70.62	61.44	67.52	65.68	53.38	81.41	78.56	65.29	70.00	59.26	81.59	72.18
2003	63.08	74.78	78.83	88.14	61.15	67.70	65.49	51.61	69.65	76.06	64.50	72.09	59.71	80.96	72.69
2004	63.82	76.89	78.47	76.25	60.93	67.65	66.71	50.91	70.48	75.43	65.29	72.38	60.57	87.24	73.46
2005	63.97	76.81	76.10	92.33	58.58	67.26	66.25	50.71	69.72	74.72	65.26	70.53	61.00	89.70	73.98
2006	63.60	77.67	75.32	91.12	57.91	66.95	69.78	50.91	68.35	74.55	64.95	68.16	61.32	77.29	72.08
2007	63.73	78.97	75.19	80.51	57.95	66.38	67.84	51.36	68.25	70.29	64.92	68.57	61.29	79.80	72.25
2008	64.07	78.72	74.47	78.90	57.23	66.41	64.36	51.32	71.91	69.49	65.11	68.67	62.40	84.61	73.27
2009	63.06	79.05	74.38	79.00	59.77	66.06	64.99	49.07	68.72	72.80	65.50	68.89	62.11	88.69	72.76
2010	63.98	77.33	73.84	77.29	61.59	65.75	66.22	49.29	70.93	78.84	67.95	69.08	61.94	92.15	71.38
2011	65.17	76.91	74.41	78.24	62.10	65.81	65.28	49.85	71.26	79.31	69.28	74.05	62.30	98.99	72.89
2012	65.33	75.18	73.54	74.43	62.01	65.43	64.70	50.21	73.48	79.49	69.67	83.14	62.09	96.75	71.73
2013	65.44	75.05	75.13	72.53	62.71	65.43	64.73	50.44	71.45	80.35	70.03	93.33	62.58	94.68	73.31
2014	65.37	77.61	75.12	73.32	62.38	65.14	65.09	50.94	69.63	80.24	70.77	97.48	62.61	100.00	74.94
2015	64.99	73.89	71.96	72.58	61.44	64.59	64.46	51.87	66.45	86.94	68.49	92.46	61.67	92.04	73.87
2016	64.57	73.48	72.01	79.44	63.18	65.04	64.90	51.90	66.79	86.08	68.07	69.18	62.28	86.90	71.57
2017	65.54	72.69	72.62	88.03	63.23	65.34	66.24	51.92	68.72	87.14	68.18	67.21	62.70	89.93	71.95
2018	65.58	73.26	72.94	82.25	63.70	65.40	66.09	51.71	69.02	86.43	68.93	69.50	62.85	89.52	71.35
2019	65.96	71.98	72.41	78.72	64.08	65.60	64.56	51.62	68.45	95.17	67.77	69.32	62.82	93.58	71.83
2020	66.01	71.49	75.68	70.85	64.48	65.26	65.25	51.56	68.65	100.00	66.75	67.62	63.07	92.90	72.74
2021	66.77	72.13	77.84	69.15	67.68	65.47	65.85	52.44	69.38	97.16	68.72	70.23	63.58	97.80	74.04
2022	66.65	71.90	77.05	70.78	67.20	66.37	64.41	52.47	70.00	99.24	70.12	69.18	63.33	97.48	72.12

Table S.8. Efficiency scores (%) for NRES_RES model (Middle 15 countries).

Years	France	Germany	Greece	Hungary	India	Ireland	Israel	Italy	Japan	South Korea	Latvia	Lithuania	Luxembourg	Malta	Mexico
1995	100.00	80.68	72.37	63.62	59.96	79.18	67.12	92.26	100.00	64.80	72.68	62.82	100.00	70.23	76.43
1996	99.92	81.15	72.01	63.09	60.42	76.94	67.49	100.00	97.22	65.06	65.16	62.85	100.00	68.95	71.53
1997	98.30	80.13	72.88	63.15	60.05	76.15	68.16	97.89	92.80	64.71	66.19	62.86	96.51	71.71	70.65
1998	96.12	81.59	67.91	63.02	59.95	74.02	69.09	97.06	91.34	64.09	63.38	62.56	100.00	70.79	69.13
1999	90.72	80.20	66.89	62.51	58.88	72.01	69.01	92.29	96.93	65.62	64.39	64.13	100.00	73.17	70.82
2000	82.80	76.08	65.61	62.23	59.21	71.41	70.49	82.73	100.00	65.59	64.00	66.87	100.00	71.00	71.60
2001	81.15	77.27	65.77	62.79	57.15	71.52	70.25	82.11	95.92	65.05	62.84	65.46	96.46	73.41	73.77
2002	84.10	82.69	66.69	63.72	57.65	74.59	68.53	80.26	93.42	65.88	64.28	65.91	85.42	100.00	72.76
2003	87.29	86.55	66.90	64.59	57.84	77.15	69.57	83.72	95.87	66.18	64.58	66.45	89.37	71.71	69.15
2004	89.15	88.77	68.19	65.35	56.76	78.93	69.84	84.31	98.99	66.89	64.01	66.01	87.95	72.00	68.23
2005	86.21	85.61	71.04	65.56	55.97	81.30	68.91	80.81	97.28	68.28	63.79	65.75	87.81	69.04	68.41
2006	84.26	80.89	68.19	65.50	55.63	79.17	67.99	78.91	92.68	68.89	63.64	65.05	94.47	68.88	67.67
2007	84.57	82.57	67.11	66.21	55.16	79.81	67.65	79.90	89.87	69.31	65.31	65.20	95.47	68.84	66.87
2008	84.07	82.64	68.92	66.93	54.63	76.11	69.09	82.22	93.62	66.66	67.07	66.74	100.00	75.27	65.73
2009	85.27	82.40	71.69	66.11	54.68	80.61	69.64	83.73	94.94	64.89	69.05	73.40	96.68	77.40	64.52
2010	81.00	79.05	76.73	68.09	55.69	86.41	69.39	80.27	100.00	66.18	69.10	73.04	100.00	71.52	64.94
2011	81.47	79.48	90.30	68.99	55.04	98.80	68.42	82.47	100.00	66.91	66.58	73.45	100.00	77.47	64.47
2012	78.38	77.30	95.23	68.89	54.80	79.72	67.34	83.07	100.00	67.27	65.46	74.58	94.30	76.42	64.28
2013	80.08	78.23	97.81	67.82	55.58	85.20	69.26	89.06	92.28	68.56	66.73	74.55	100.00	86.40	65.48
2014	84.35	79.29	100.00	67.03	56.00	82.05	71.13	92.16	91.19	70.03	68.61	75.29	100.00	85.67	66.05
2015	80.18	75.59	98.59	65.64	56.66	76.94	71.35	83.19	89.13	69.95	67.87	70.41	95.04	73.52	64.49
2016	79.50	75.64	91.16	67.73	57.05	71.46	70.65	82.45	97.15	70.37	70.99	70.68	100.00	83.10	63.76
2017	78.60	75.97	87.82	65.68	57.31	74.83	72.15	82.05	97.00	71.36	70.29	71.31	97.29	89.48	64.31
2018	79.82	76.78	97.02	64.86	56.23	79.75	71.86	81.84	98.54	72.06	68.85	71.02	100.00	94.65	64.85
2019	78.13	76.40	100.00	63.91	56.90	81.48	72.87	80.25	99.68	71.32	68.98	70.06	93.52	90.25	65.61
2020	79.67	76.39	94.62	63.97	57.50	85.63	74.30	80.59	99.79	71.16	69.15	69.92	100.00	86.59	66.22
2021	78.03	77.65	93.30	64.11	57.18	99.32	74.36	78.32	100.00	72.71	70.12	70.99	100.00	90.02	66.25
2022	74.54	76.51	91.37	63.63	57.53	100.00	73.28	74.49	91.44	71.14	70.91	71.89	100.00	75.41	65.90

Table S.9. Efficiency scores (%) for NRES_RES model (Last 15 countries).

Years	Netherlands	New Zealand	Poland	Portugal	Romania	Russia	Slovakia	Slovenia	South Africa	Spain	Sweden	Switzerland	Türkiye	United Kingdom	United States
1995	83.10	73.73	66.75	70.95	60.67	59.63	60.44	66.54	69.11	76.07	100.00	100.00	64.02	85.04	68.44
1996	79.06	74.72	63.76	71.22	59.70	60.29	57.88	65.76	70.79	78.16	100.00	100.00	63.40	84.05	68.56
1997	78.03	72.75	62.11	68.37	60.29	61.58	57.19	64.95	71.39	73.69	99.95	95.60	62.96	100.00	69.18
1998	79.44	72.65	61.88	67.93	62.60	62.48	57.35	65.13	67.80	72.50	97.65	96.73	66.46	97.89	69.57
1999	77.56	70.82	61.63	66.98	62.90	63.90	59.68	64.88	83.36	69.60	95.41	94.30	68.11	98.27	69.50
2000	76.04	69.61	61.93	66.24	62.07	61.57	61.49	64.16	96.35	67.51	91.33	90.69	65.78	92.17	69.34
2001	76.39	68.03	63.82	66.45	60.85	60.34	60.40	64.10	94.85	67.66	85.27	89.50	67.02	88.60	69.73
2002	79.38	69.09	65.15	66.81	60.85	61.07	61.28	65.04	100.00	67.59	86.87	90.63	66.17	88.81	70.42
2003	83.31	69.25	65.11	69.67	60.50	60.94	63.43	65.72	100.00	68.40	93.65	93.48	66.11	92.21	69.23
2004	84.70	69.72	65.00	70.86	61.64	61.40	64.35	65.76	100.00	68.75	97.72	93.35	64.80	100.00	68.57
2005	83.77	69.19	65.08	70.02	62.34	62.09	63.61	65.29	91.01	68.46	95.58	92.12	65.00	96.66	67.75
2006	82.22	68.63	64.29	71.36	61.60	62.01	64.22	64.86	64.83	68.46	93.44	90.51	63.75	94.17	67.53
2007	77.63	70.19	63.90	72.73	59.90	61.21	64.86	65.12	62.58	68.85	93.63	91.87	63.88	96.38	67.65
2008	81.79	70.07	64.38	72.99	60.00	61.46	65.45	65.22	60.27	70.10	91.88	93.92	64.51	94.73	68.48
2009	79.97	72.82	63.98	72.99	63.23	60.04	67.82	66.61	61.57	72.63	92.21	91.64	65.17	93.71	71.14
2010	80.17	75.61	64.86	73.84	63.07	60.84	66.85	68.38	63.26	73.93	91.41	91.78	64.33	91.56	70.87
2011	81.37	77.16	64.69	78.08	62.49	62.00	65.28	69.98	63.49	77.40	95.94	100.00	62.86	98.97	70.36
2012	81.92	74.54	64.84	84.16	62.10	62.25	67.72	69.93	62.88	78.21	94.82	96.05	63.13	97.34	69.84
2013	83.15	74.32	65.29	94.70	63.91	62.33	67.51	69.60	62.01	83.96	100.00	97.65	63.35	98.42	69.26
2014	85.64	73.32	64.88	92.73	64.30	61.84	68.29	71.55	61.79	82.33	99.21	100.00	62.68	99.24	68.62
2015	71.76	70.87	63.91	80.54	63.44	60.38	64.89	70.10	61.63	76.53	91.19	97.85	62.07	94.13	69.00
2016	74.28	72.84	64.31	81.42	64.57	59.20	66.48	70.85	61.29	77.34	91.16	97.04	61.84	88.32	69.31
2017	74.79	72.68	64.86	74.79	65.12	59.79	66.27	70.13	62.72	75.20	89.05	96.86	60.63	86.85	69.28
2018	75.79	72.03	64.61	75.74	66.69	60.39	67.05	69.96	63.09	75.05	90.94	95.77	59.67	89.08	68.92
2019	74.71	71.26	64.75	76.07	65.96	60.15	66.97	69.85	63.20	74.65	93.61	95.09	61.16	88.63	69.45
2020	75.15	72.06	65.09	75.24	65.84	59.43	68.55	70.78	64.29	74.91	90.95	95.72	59.60	91.65	69.61
2021	77.88	71.65	66.86	74.99	65.85	61.21	69.59	70.99	65.90	77.12	92.74	99.50	60.00	98.49	70.66
2022	77.82	69.44	66.91	74.64	65.52	61.48	68.49	69.29	64.76	76.31	85.33	100.00	60.08	93.36	71.73