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Green Energy Pathways Towards Carbon Neutrality

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Abstract

Trying to reach carbon neutrality is by no means plain sailing in times of energy crisis, price volatility, and war. The European Green Deal (EGD) prioritizes green pathways, but it is not enough when it copes with greenhouse gases (GHGs). The present research utilizes the Malmquist–Luenberger productivity index (MLPI) to estimate advancements in total factor productivity (TFP) in the European Union (EU). The study uses panel data from 1995 to 2019, in addition, there is comparison between two periods: 1995 – 1996 and 2018 – 2019, would provide important information about TFP progress or recession during a turbulent European era. Two MLPI models are applied, one that utilizes only non-renewable energy sources (NRES), while the other adopts renewable energy sources (RES). Encompassing inputs such as: electricity generation, labour force, and gross fixed capital formation (GFCF); desirable output: gross domestic product; and undesirable outputs: carbon dioxide (CO_2) and methane (CH_4). There is average productivity progress, more specifically the MLPI average productivity for NRES and RES is 2.14% and 7.34% respectively, meaning that the RES adoption leads to greater productivity performance by almost three times. This novel analysis might offer useful and practical information to policymakers through the measuring of TFP in order to effectively attain and accomplish carbon neutrality objectives.

Keywords Climate change · Carbon neutrality · Greenhouse gases · Malmquist-Luenberger productivity index · Nonrenewable energy sources · Renewable energy sources · Sustainable development

Abbreviations

BBC model	Banker Charnes and Cooper
CCR model	Charnes Cooper Rhodes

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DEA	Data envelopment analysis
EGD	European green deal
GHGs	Greenhouse gases
NG	Natural gas
PVs	Photovoltaics
SOx	Sulfur oxides
UN	United Nations
CCD model	Caves Christensen and Diewert
CRS	Constant returns to scale
DGP	Data generating process
EU	European Union
LNG	Liquified natural gas
NOx	Nitrogen oxides
RES	Renewable energy sources
TFP	Total factor productivity
VOCs	Volatile organic compounds
GFCF	Gross fixed capital formation
CSP	Concentrating solar power
DMUs	Decision making units
GDP	Gross domestic product
MLPI	Malmquist Luenberger productivity index
NRES	Non-renewable energy sources
SDGs	Sustainable development goals
VRS	Variable returns to scale

1 Introduction

The path towards *carbon neutrality* in the European Union (EU) and the United Kingdom (UK) is a subject of great concern. Nevertheless, keeping in pace with the European Green Deal (EGD) is by no means plain sailing for many EU members, specifically in a tumultuous era of full of enigmas: energy crisis, inflation, climate change, and war. Typically, copying with climate change without trying to achieve carbon neutrality is a bit of oxymoron, hence it is understandable that this transition is crucial for building a sustainable future.

Moreover, energy poverty levels are rising due to inflating prices in energy, making unsustainable the modern way of life (González-Eguino 2015; Halkos and Gkampoura 2021; Halkos and Aslanidis 2023a). Greenhouse gases (GHGs) pose also robust strains on climate change mitigation and adaptation, especially the CO_2 and CH_4 emissions are multiplying based on a plethora of factors, such as the rampant consumption and production patterns and the ''unsustainable'' economic growth (Barbier 2011; Cock 2014; Nyborg et al. 2016; Vertakova and Plotnikov 2017; Acheampong 2018; Karydas and Xepapadeas 2019; Menuet et al. 2020; Xepapadeas 2021; Koundouri et al. 2021; Cai et al. 2022; Chatzistamoulou and Koundouri 2022; Fotopoulou et al. 2022). Additionally, energy demand can be as well a subject of different forcing factors, such as population growth and economic activity (Timilsina 2020). Hence, considering all of the above, how can carbon neutrality be a tangible future and not a utopian one?

Green economy could strike a balance between all the previous enigmas by promoting carbon neutrality and enabling universal access to energy. Green economy exploits different types of energy sources, either renewable energy sources (RES), or non-renewable energy source (NRES). The present study would examine solar, wind, and hydroelectric energy from the RES perspective (Denholm et al. 2010; Ellabban et al. 2014; Mac Kinnon et al. 2018; Halkos and Gkampoura 2020), whereas NRES are composed by coal, oil, natural gas, and nuclear energy. Moreover, the natural gas (NG) and specifically the liquified natural gas (LNG) would be also discussed as important intermediates in the green transition era (Elgohary et al. 2014; Thomson et al. 2015; Mac Kinnon et al. 2018; Lindstad and Rialland 2020; Song et al. 2020).

European Commission has paved the way in delivering proper institutional framework on green energy transition, to exemplify: the EU solar energy strategy; strategy on heating and cooling; wind energy developments and EU nature legislation; offshore renewable energy; and especially the REPowerEU plan for copying with the Russian invasion in Ukraine and its implication in NG supply (EC 2016, 2022; E.C. 2020a, b, 2022; D.N.V. 2022; I.E.A. 2022; Halkos and Aslanidis 2023b). Though how can *electricity generation* be measured for pathfinding a proper green transition without emitting GHGs and by going towards sustainable development?

A proposed methodology is by estimating the total factor productivity (TFP). TFP might be a happy medium in bridging electricity generation with low GHGs emissions, measuring it ultimately the clean energy generation performance. Furthermore, TFP is a factor of great attention when having to scale up energy supply chains in order to achieve affordable, secure, and sustainable energy development (I.E.A. 2022; IRENA 2022).

The present study would (i) emphasize the main advances in RES and NRES in order to achieve carbon neutrality; (ii) employ linear-programming methodology to cope with undesirable outputs; (iii) delve into TFP and its intrinsic parts; and (iv) compare two MLPIs with NRES and RES to distinguish possible interrelations on halving GHG emissions. The structure of the study consists of the following sections: 1.1. would accent the importance of NRES (i.e., coal, oil, NG and nuclear) as traditional energy sources and the significance of RES (i.e., solar, wind, and hydro) as green energy solutions concerning the final stage of green transformation; while Sect. 1.2. contains the main advancements on data envelopment analysis (DEA) and the theory of MLPI. Data and methodology are presented on Sect. 2; whereas the main results and discussion aspects are expanded on Sects. 3 and 4 respectively; at the end, on Sect. 5 the concluding remarks and central policy implications are being vindicated.

1.1 Answering Global Energy Conundrums: Carbon Neutrality

Energy demand is advancing in parallel with economic growth and peoples' welfare (Timilsina 2020), accordingly, energy resources can be categorized into ''primary'' (e.g., solar or wind) and ''secondary'' (e.g., NG). The former can directly produce energy services, whereas the latter need an ''energy transformation'' for delivering secondary energy commodities. Nevertheless, rebound – direct or indirect – effects are looming, representing the discrepancies between rising energy efficiency and not an expected diminishing energy consumption. The main reason of rebound effects is the augmented energy use due to cheaper complementary energy commodities (Gillingham et al. 2016; Bruns et al. 2021; Saunders et al. 2021).

GHGs play also a significant role in energy transition and sustainable development, consequently regulatory authorities try to pose restrictions on GHG emission to combat climate change. The EU is on track to green transformation through on the EGD framework which aims the halving (based on 1999 levels) and zeroing of GHGs by 2030 and by 2050 respectively (E.C. 2019; IRENA 2022). In parallel, the International Maritime Organization I.M.O. (2018) has a bit similar pathway, as it has put the target at halving GHGs by 2050 (based on 2008 levels). However, it is the challenge of reducing oil consumption that dampers green transition in transport sector (E.E.A. 2020). Therefore, the main achievements in RES and NRES technologies are going to be analyzed.

RES can significantly contribute to green transition. Though, variability and uncertainty are intrinsic parts of the photovoltaics (PVs) and wind turbines, this is also one reason why they are being called as ''*intermittent*''. Thus, there is no stable electricity production due to external factors, hence, the necessity of energy storage is of utmost importance nowadays (Denholm et al. 2010).

Solar energy can be categorized into three general infrastructures: PVs, concentrating solar power (CSP), and solar heating. Firstly, PVs can be characterized by high efficiency even with low levels of sunlight, pivotal for impoverished communities and developing countries (Ellabban et al. 2014). The rapid conversion of sunlight into electricity can be described also as a great potential for constructing sustainable regimes (Halkos and Gkampoura 2020). However, PVs have among the higher emissions among the RES forms, but excessively lower emissions than NRES (Mac Kinnon et al. 2018).

Secondly, CSP has lower efficiency standards than PVs, when there is ramping events or no sunlight, but high efficiency can be achieved via thermal energy storage (Denholm et al. 2010). The storage and backup systems are necessary for CSP as well (Ellabban et al. 2014). Though there are high GHG emissions linked to the life cycle of the CSP plant design, due to the extracted materials used in such infrastructure (Mac Kinnon et al. 2018). Thirdly, solar heating is a very effective way of utilizing solar energy for covering basic modern amenities (Ellabban et al. 2014).

Apparently, hydro-electricity is a traditional form and a RES yet. Apergis et al. (2016) found that as the significance of hydropower has become more pivotal for economic growth, as it is a non-polluting source. Unequivocally, hydroelectricity in Europe is confronted with some challenges, such as the creation of hydropower plants in vulnerable ecosystems, the integration in energy markets, and political avoidance to RES infrastructure (Wagner et al. 2019; Tomczyk and Wiatkowski 2020). Next in order, the NRES forms of NG and LNG are going to be discussed.

NRES include nuclear power and fossil fuels, both of which have negative and positive aspects. Nuclear energy,[1] for example, is important for the transition to a sustainable future (Nathaniel et al. 2021) and can lead to lower CO_2 emissions (Saidi and Omri 2020). In addition, unsurprisingly, fossil fuels are also crucial for the economic growth of the previous decades due to their low-cost technology and uncomplicated transformation to electricity (Kanat et al. 2022).

Nevertheless, NRES have detrimental impacts on nature and people as well, for instance, Burgherr et al. (2012) monitored the severity of accidents on NRES energy chains such as fatality rates and subsequent economic losses. Apparently, the GHG emissions are

[1] Nuclear energy can be categorized to the NRES due to the material used in such power plants, even though it is a low-emission practice (National Geographic 2024).

the main drawback of fossil fuels, however can the transitional fuels such as NG and LNG be a compromise?

Regarding the NRES such as NG and LNG there are also advancements and implications that ought to be mentioned. Undoubtedly, the CH_4 emissions are a matter of great concern, especially from old-fashioned ship engines, on contrary, the novel LNG engines can reduce global warming issues yet (Balcombe et al. 2021). It has been also reported that volatile organic compounds (VOCs) are emitted by LNG-fueled vehicles that put pressure on air quality (Song et al. 2020). There are also alerting issues on terms of safe storage of NG and specifically of LNG due to labour-related accidents in infrastructure and transportation (Elgohary et al. 2014). For instance, Not-in-my-backyard (NIMBϒ) syndromes are also apparent on such infrastructure.

On the other hand, NG and LNG have a great potential in enabling the transition to renewable fuels, such as the low criteria pollutants in relevance to rest fossil fuels (Mac Kinnon et al. 2018). As stated before, the IMO took strict regulations for sulfur and nitrogen oxides (SOx and NOx) (Lindstad and Rialland 2020). The most important milestone in LNG usage is the competitiveness in maritime – global and regional – demand by reducing GHGs and enabling port growth (Thomson et al. 2015).

1.2 Measuring Total Factor Productivity Towards Carbon Neutrality

Productivity growth has been thoroughly examined under different scientific areas, for instance via non-parametric and linear programming methods. Leading publications were made by Solow, by Farrell's, and by Charnes-Cooper-Rhodes (CCR model). In more detail, the nexus between productivity growth and technical changes have been explored by (Solow (1957), while methods of measuring production efficiency scores under the scope of non-parametric analysis were proposed by Farrell (1957). Moreover, linear programming analysis via DEA considered the relative efficiency of decision-making units (DMUs) (Charnes et al. 1978).

There are some typical axioms that should be checked as free disposability, convexity, and ''constant-returns-to-scale'' (CRS). The CCR publication paved the way for CRS, whereas a different approach is the ''variable-returns-to-scale'' (VRS) proposed by Banker, Charnes, and Cooper (BBC model) (Charnes et al. 1978; Banker et al. 1984).

Briefly, these two models have two distinct characteristics on the matter of proportionality change in variables and referring to the CRS or VRS options. Purporting that the CRS utilizes proportional change on the examined variables, also this model is preferred for constant variables, on the other hand, the VRS is indifferent of proportional change, it is also applicable to non-constant returns to scale (Halkos and Petrou 2019a). It should be also added that a DMU might represent augmented productivity performance not only due to efficiency improvements, but also because of taking advantage of technological changes and scale economies (Coelli et al. 2005).

The theoretical background of Solow on explaining productivity performance was altered by the publication of Caves, Christensen, and Diewert (CCD), who modified the element of time derivative of the production function for advancing index numbers[2]

[2] Based on the economic theory, some assumptions referring to index numbers such as that the observed DMUs between two periods are technically and allocatively efficient, with cost-minimizing and revenue-maximizing performances, or rarely based on "constrained optimization" of revenues with cost constraints (Coelli et al. 2005).

(Caves et al. 1982a, b). The reason of altering was done because index numbers involves ''a discrete approximation to the time derivative'', thus the CCD model introduced a similar nomenclature such as the Malmquist productivity index (MPI) honoris causa on Malmquist's publication (Malmquist 1953). Moreover, a phenomenon of great seriousness is that on productivity growth the ''Solow residual'' is looming. This phenomenon shades light on the unexplained output changes due to input changes represented in the ''technological change'' element (Boussemart et al. 2003). In general, TFP measures if a DMU reaches the world frontier[3] through efficiency change (catching-up), and shifts (innovation) on the world frontier due to technological change. However, is there any problem referring to a well-rounded model?

Another aspect that on should bear in mind is what Simar and Wilson stated as "bias by construction" (Simar and Wilson 1998; Halkos and Petrou 2019b; Moradi-Motlagh and Emrouznejad 2022). An escape of such a riddle is the running of a *bootstrap technique* that smooths the outcomes of a DEA model. A bootstrap is subject of Efron's bootstrap technique that was a simulation of a Data Generating Process (DGP), a DGP is actually the construction of pseudo-data set (Coelli et al. 2005; Halkos and Petrou 2019a).

Malmquist-Luenberger productivity index (MLPI) incorporates the Malmquist notion, however it takes into account distance function in order to enhance input minimization and output maximization (Chambers et al. 1996; Boussemart et al. 2003; Oh 2010; Wang et al. 2020). MPI and MLPI have fundamental differences. firstly the choice of distance functions, secondly the incorporation of the economic literature basis of the indices, and thirdly the choice of the index decomposition in a multiplicative or additive[4] way (Chambers et al. 1996; Boussemart et al. 2003). The previous reasons constitute the MLPI a suitable way of dealing with undesirable outputs (Chung et al. 1997; Jeon and Sickles 2004).

A recent review by Chachuli et al. (2020) illustrated that the importance of DEA on the renewable energy sector and the need to expand the DEA applications in the future. On this basis, we aim to apply a DEA methodology in order to check the productivity performance on the NRES and RES energy sectors. In a similar way, Wang et al. (2021) evaluated the renewable energy production capabilities based on window DEA and Fuzzy TOPSIS Model. Kim et al. (2015) found that wind power is the most efficient renewable energy form in Korea, whereas Kolagar et al. (2020) found that the adoption of RES via hybrid DEA-FBWM might be lead to better planning on the RES energy sector.

Above all, the capabilities of DEA methodology and its extension in copying with undesirable outputs has necessitated the proliferation of studies in operations research (OR) and management science (MS) that try to make this enigma a common practice. For instance, some ways to deal with undesirable outputs are (i) the disregarding of bad outputs on the production function, (ii) the utilization of bad outputs in a way such as input, (iii) handling undesirable outputs with non-linear methodology, and (iv) by managing via structural transformations (Halkos and Papageorgiou 2014; Halkos and Petrou 2019a; Wang et al. 2022). In our analysis, two MLPI models utilize electricity generation, either from NRES or RES, but both models have as undesirable outputs the CO_2 and CH_4 emissions. In essence, a common way of interpreting MLPI outcomes is by describing their values: if the TFP take values > 1 (< 1) then we have productivity prosperity (recession), but when $= 1$, there is stagnation.

[3] The world frontier of the present study is EU-27 member states.

[4] Multiplicative measures the relative change, while additive calculates the absolute change.

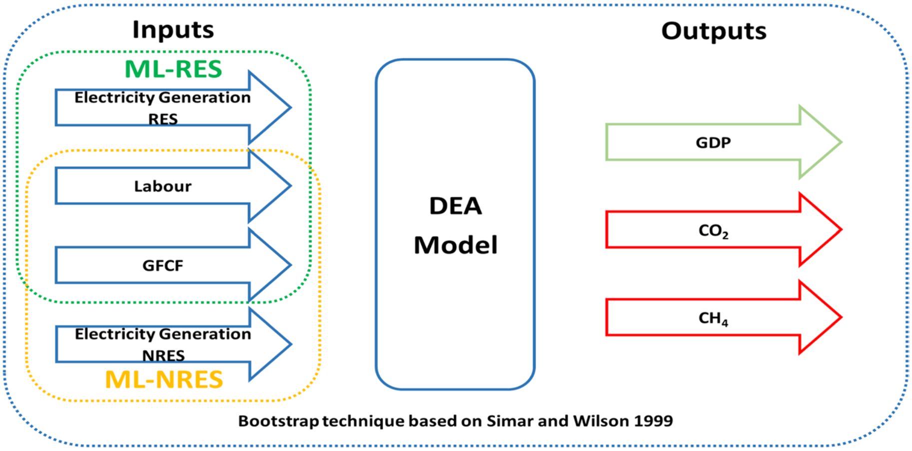

Fig. 1 Methodology plan for measuring Malmquist-Luenberger productivity index for NRES and RES

2 Data and Methodology

The data were collected from the World Bank Group and Our World in Data for the EU member-states and span throughout the period 1995–2019 and panel data analysis was applied. Furthermore, the present study utilises the European countries as DMUs, to distinguish possible interconnections between the productivity performance of these countries based on their GHGs emissions as in Fig. 1.

Further, the EU-27 countries have been categorized geographically into four groups as in Fig. 2, only Estonia has been left out as there was no data availability. In our analysis the DEA formulation (Fig. 1) is defined with the following parameters, as inputs: electricity generation (GWh); labour (total); Gross Fixed Capital Formation (GFCF) (current US $). It should be mentioned that the first model is based on electricity generation from NRES (i.e., nuclear, oil, natural gas, and coal), while the second model refers exclusively to RES (i.e., hydro, wind, solar etc.). Moreover, the desirable output is Gross Domestic Product (GDP) (current US $), whereas the two undesirable outputs are: CO_2 (kt) and CH_4 (kt of CO_2 equivalent).

The adoption of RES has risen from 1995 to 2019 as it can be seen on Fig. 3. The inner circles show the energy generation in 1995, which was basically generated from NRES for most of the cases. On the contrary, the NRES percentage has been reduced as shown at the outer circles that show the energy generation structure in 2019, with some countries, inter alia, Greece, Lithuania, Luxembourg, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden to gain momentum on RES adoption.

2.1 Measuring Productivity via the Use of Various Indices

A way of comparing a DMU's performance is through productivity indices, for instance the present study would apply the two MLPI scenarios. Should these indices undergo a bootstrapping process, then the examination of the interconnections of two differences might be possible. It is important to delve into these differences, thus, firstly the difference between the real and the estimated values of the productivity indices, and secondly the difference

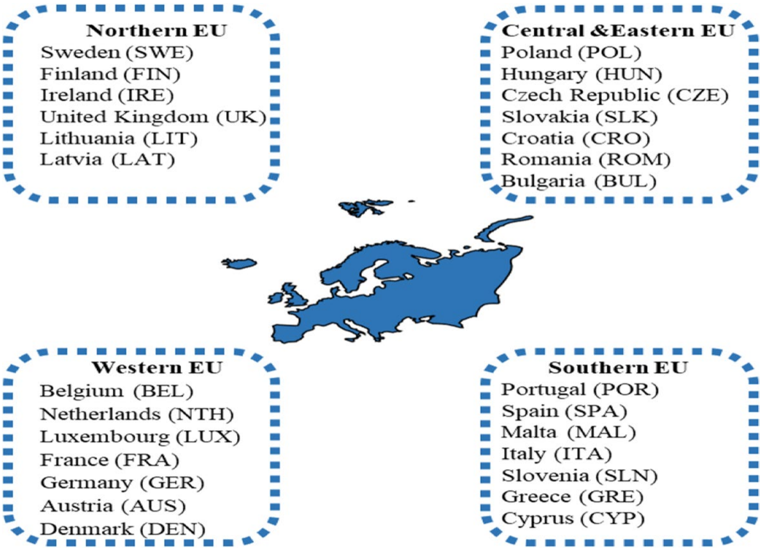

Fig. 2 The categorization of EU member-states into four geographical groups

between the bootstrapped and the estimated values. Then might be crucial for checking the statistically significant difference between these two distinctions.

2.2 The Production Frontier Technology

If a DMU is set on the boundary of the production curve, then it is technically efficient (Coelli et al. 2005). The production function S^t considers the transformation of inputs $x^t \in \mathbb{R}^N_+$, into outputs $y^t \in \mathbb{R}^M_+$, where $\mathbb{R}^{N+M}_+$ is the Euclidean space.

$$S^t = \{ \left(x^t, y^t\right) : x^t can\ produce\ y^t \} \tag{1}$$

Some axioms referring to the production function should be followed in order to define an appropriate output distance function.[5] This production set could be defined for the input correspondence ($\forall x \in S^t$) and for output correspondence ($\forall y \in S^t$) as (Simar and Wilson 1998):

$$\begin{aligned} X(y) &= \left\{ x^t \in \mathbb{R}^N_+ | (x, y) \in S^t \right\} \\ Y(x) &= \left\{ y^t \in \mathbb{R}^M_+ | (x, y) \in S^t \right\} \end{aligned} \tag{2}$$

Therefore, based on two publications of Farrell (1957) and Simar and Wilson (1998), there are efficiency boundaries which are subsets of the above $X(y)$ and $Y(x)$, defined as $\partial X(y)$ and $\partial Y(x)$: [6]

5 For more information, please, see: (Shepard 1970).

6 The terms "$0 < \theta < 1$" and "$\beta > 1$" represent the feasibility of proportionately reduction input(s) (or increase of output(s)) if y^t(orx^t) were achieved in an efficient manner (Simar and Wilson 1998).

Fig. 3 Electricity generation percentage of RES (green colour) and NRES (orange colour) in EU-27 countries, the inner circle presents the 1995 levels, whereas the outer circle illustrates the 2019 levels

$$\begin{aligned} \partial X(y) &= \left\{ x^t | x^t \in X(y), \theta x \notin X(y) \forall\ 0 < \theta < 1 \right\} \\ \partial Y(x) &= \left\{ y^t | y^t \in Y(x), \beta y \notin Y(x) \forall\ \beta > 1 \right\} \end{aligned} \tag{3}$$

In such a way, the measures of efficiency of a specific point (x^t, y^t) are:

$$\begin{aligned} \theta^t &= \min\left\{\theta | \theta x^t \in X\left(y^t\right)\right\} \\ \beta^t &= \max\left\{\beta | \beta y^t \in Y\left(x^t\right)\right\} \end{aligned} \tag{4}$$

Probable outcomes of – input and output – efficiency might be supposed by reaching $\theta^t = 1$ and $\beta^t = 1$ accordingly. Having these nexuses in mind, one can reach a feasible production frontier, moreover the above equations are necessary for running a bootstrap technique for alleviating some imminent problems of statistical inferences in DEA.

2.3 Malmquist–Luenberger Productivity Index

The MLPI also follows axioms referring to directional distance function via the use of a broader directional vector $\left(-g_i, g_o\right)$ that is parallel to $g_i = x$ (input/s) and $g_o = y$ (output/s) (Chambers et al. 1998). On the following relations there are – input and output – proportional distance functions accordingly:

$$\begin{aligned} D^i_{S(t)}\left(x^t, y^t\right) &= \max_{\delta}\left\{\delta \geq 0; \left((1-\delta)x^t, y^t\right) \in S(t)\right\} = 1 - E^i_{S(t)}\left(x^t, y^t\right) \\ D^o_{S(t)}\left(x^t, y^t\right) &= \max_{\delta}\left\{\delta \geq 0; \left((1-\delta)x^t, y^t\right) \in S(t)\right\} = 1 - E^o_{S(t)}\left(x^t, y^t\right) \end{aligned} \tag{5}$$

where, $E_{S(t)}(x^t, y^t)$ is the Debreu-Farell efficiency measure, that is the inverse of Shephard's distance function (Boussemart et al. 2003). The decomposition of MLPI is the following:

$$\begin{aligned} MLPI\left(x^t, y^t, x^{t+1}, y^{t+1}\right) = &\left[D_{S(t)}\left(x^t, y^t\right) - D_{S(t+1)}\left(x^{t+1}, y^{t+1}\right)\right] \\ &+ \frac{1}{2}\left[\left(D_{S(t+1)}\left(x^{t+1}, y^{t+1}\right) - D_{S(t)}\left(x^{t+1}, y^{t+1}\right)\right)\right. \\ &\left.+ \left(\left(D_{S(t+1)}\left(x^t, y^t\right) - D_{S(t)}\left(x^t, y^t\right)\right)\right)\right] \end{aligned} \tag{6}$$

This decomposition consists of two square brackets. Firstly, there is the proportional distance function between two time periods (period t to period t + 1) this difference presents the technical efficiency change. Secondly, the other bracket represents the ''arithmetic mean'' of the two other differences, which is ultimately the technological change (Boussemart et al. 2003).[7] Furthermore, this decomposition[8] is also composed of two new components, i.e., efficiency change (EC) and technological change (TC). Especially the EC component can be further decomposed into: pure efficiency change (PC) and scale change (SC). The element of PC enables the explanation of improvements in core efficiency, while SC represents the returns-to-scale effects (Babu and Kulshreshtha 2014).

3 Results

The estimation of TFP was done through 1000 replications under a bootstrap method introduced by Simar and Wilson, considering time-dependence (Simar and Wilson 1999). In addition, the panel data followed directional distance functions based on the

[7] In parallel with the above: $L\left(x^t, y^t, x^{t+1}, y^{t+1}\right) = EC \times TC$ (Boussemart et al. 2003).

[8] Equally: $MLPI(x^{t+1}, y^{t+1}, x^t, y^t) = EC \times TC = (PC \times SC) \times TC$, it should be mentioned that EC was calculated under CRS, while PC under VRS (Färe et al. 1994).

Table 1 Descriptive statistics

	GFCF Current USD	LABOUR Total	NRES GWh	RES GWh	CO_2 kt	CH_4 kt of CO_2 equivalent	GDP Current USD
Min	547,397,534.42	147,591.00	197.13	0.00	1,352.30	184.77	3,461,332,684.82
Mean	111,523,280,681.92	8,802,555.85	92,583.02	22,660.35	136,945.67	18,516.26	537,623,561,942.55
Max	837,224,709,225.88	44,433,744.00	550,988.24	194,757.70	904,337.40	117,551.36	3,974,443,355,019.60
STD	169,932,697,067.06	10,934,372.49	134,908.19	32,877.30	184,555.98	22,602.05	843,600,043,688.20
Observations	675						
Period	1995–2019						
No. of Countries	EU – 27						

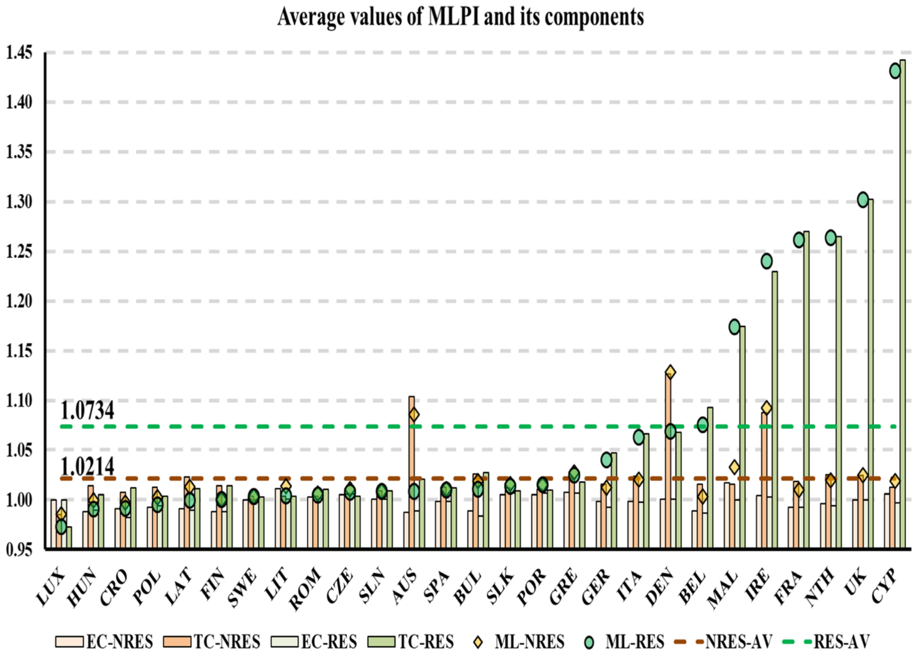

Fig. 4 Average values of the MLPI and its decomposition during the period 1995 – 2019. The NRES is illustrated in orange colour and the RES in green colour

literature. Both models have as undesirable outputs the GHGs, either generated from NRES or RES. Table 1 illustrates the descriptive statistics.

In Fig. 4 the averages of the two MLPI models and their components are depicted. The first model includes only NRES, with an average of 2.14%, on the other hand, the second model that utilizes exclusively RES has greater average productivity performance that reached 7.34% progress, almost three times greater than NRES. The countries that showed the greatest RES productivity performance are Cyprus, the UK, Netherlands, France, Ireland, Malta, and Belgium.

Additionally, one important aspect is that the countries with higher productivity performance via the RES utilization is based on TC (i.e., innovation, the deep-coloured columns) instead of EC (i.e., catching-up actions, the light-coloured columns). In comparison to Fig. 3, Fig. 4 illustrates that most of the countries below show a similar performance, as the adoption of RES has significantly impacted some European energy sectors. In contrast, only few countries have high NRES utilization and productivity performance, such as Austria, and Denmark (Table 2 and 3).

The TFP is necessary to show how a DMU has performed regarding the utilization of NRES and RES. Table 2 shows how TFP has altered from 1995 to 2019 either in NRES or RES. The greatest NRES TFP for the year 1995 can be found in Bulgaria, Cyprus, and Italy, whereas the lowest TFP is in Austria, Latvia, Slovakia, and Slovenia. However, this pattern changes for the year 2019 as Denmark, Greece, and Ireland showed the greatest NRES TFP, but Hungary and Austria had the lowest performance.

On the other hand, the highest performance for RES TFP for 1995 can be spotted in Slovakia, Netherlands, and Italy, whereas the DMUs with the lowest performance are

Table 2 Total factor productivity of Malmquist-Luenberger productivity indices for NRES and RES

DMU	NRES		RES	
	1995–1996	2018–2019	1995–1996	2018–2019
AUS	0.6458*	0.9549*	0.9386*	0.9549*
BEL	0.9991	0.9732*	0.7719	0.9733
BUL	2.2410*	1.0079	2.0543*	1.0286*
CRO	0.8373*	0.9574*	0.8181*	0.9626*
CYP	1.0441*	0.9973	1.0099	0.9958*
CZE	0.9960	0.9807*	0.9895*	0.9766*
DEN	0.9874	1.3468*	0.7150*	1.2110
FIN	0.9437*	1.0151	0.9437*	1.0151
FRA	0.9457	0.9744*	0.5498*	0.9742*
GER	1.0126	0.9884	0.5342*	0.9884
GRE	0.9660*	1.0440*	0.9635*	1.0440*
HUN	0.9586*	0.9241*	0.9410*	0.9176*
IRE	0.9275*	1.0266	0.9273*	1.4724*
ITA	1.0354	0.9864*	1.0360	0.9866*
LAT	0.8020*	1.0093*	0.8049*	1.0162*
LIT	0.9915	0.9698*	1.0052	0.9660*
LUX	0.9113*	0.9757*	0.9359	0.9757*
MAL	0.9574*	0.9583*	0.9865	0.6427*
NTH	0.9694*	0.9701*	0.5526*	0.9582*
POL	0.9296*	1.0014	0.9059*	1.0039
POR	1.0110	1.0134*	0.9886	1.0128
ROM	0.9243*	0.9705	0.9437*	0.9766
SLK	0.8226*	0.9793	0.8215*	0.9622*
SLN	0.9706*	0.9928	0.9705*	0.9928
SPA	1.0157	0.9879	1.0124	0.9879
SWE	1.0000	1.0129*	1.0000*	1.0129*
UK	0.9800*	1.0063	1.0052	1.0063
EU-27 mean	0.9936	1.0009	0.9306	1.0006
N. EU mean	0.9408	1.0067	0.9477	1.0815
W. EU mean	0.9245	1.0263	0.7140	1.0051
C&E EU mean	1.1014	0.9745	1.0678	0.9755
S. EU mean	1.0001	0.9972	0.9954	0.9518

The (*) denotes that there is statistically significant difference via the bootstrap technique

France, Finland, and Czech Republic. In 2019 the RES TFP greatest performance can be seen in Greece, Ireland, and Malta, whereas the lowest performance is in Lithuania.

A clearer pattern can be observed based on the percentage change of the European regions' performance, i.e. Northern (N EU), Western (W EU), Central and Eastern (C & E EU), and Southern (S EU). Regarding the NRES, the EU mean has altered from a recession of 0.64% to a progress of 0.09%, or alternatively a percentage change of 0.74%. The greatest positive percentage change was in Western EU (10.18%) followed by Northern EU (6.59%), nevertheless there was a negative pathway for Southern (–0.29%) and Central-Eastern EU (–12.69%).

Table 3 Average annual MLPI (NRES and RES) and its components in the period 1995 –2019

Years	NRES–MLPI and its determinants							RES–MLPI and its determinants						
	MLPI	EC		TC	PC		SC	MLPI	EC		TC	PC		SC
1995–1996	↓	EC	>	TC	PC	>	SC	↓	EC	<	TC	PC	>	SC
1996–1997	↓	EC	<	TC	PC	<	SC	↓	EC	<	TC	PC	<	SC
1997–1998	↓	EC	>	TC	PC	>	SC	↓	EC	>	TC	PC	>	SC
1998–1999	↓	EC	>	TC	PC	>	SC	↑	EC	>	TC	PC	>	SC
1999–2000	↓	EC	>	TC	PC	<	SC	↓	EC	>	TC	PC	<	SC
2000–2001	↓	EC	>	TC	PC	>	SC	↓	EC	>	TC	PC	>	SC
2001–2002	↑	EC	<	TC	PC	>	SC	↑	EC	<	TC	PC	>	SC
2002–2003	↑	EC	<	TC	PC	>	SC	↑	EC	<	TC	PC	>	SC
2003–2004	↑	EC	<	TC	PC	>	SC	↑	EC	<	TC	PC	>	SC
2004–2005	↑	EC	<	TC	PC	>	SC	↑	EC	<	TC	PC	>	SC
2005–2006	↓	EC	<	TC	PC	>	SC	↑	EC	<	TC	PC	>	SC
2006–2007	↑	EC	<	TC	PC	>	SC	↑	EC	<	TC	PC	>	SC
2007–2008	↑	EC	<	TC	PC	>	SC	↑	EC	<	TC	PC	>	SC
2008–2009	↑	EC	<	TC	PC	<	SC	↑	EC	>	TC	PC	<	SC
2009–2010	↑	EC	>	TC	PC	>	SC	↑	EC	>	TC	PC	<	SC
2010–2011	↑	EC	<	TC	PC	>	SC	↑	EC	<	TC	PC	>	SC
2011–2012	↑	EC	<	TC	PC	>	SC	↓	EC	<	TC	PC	<	SC
2012–2013	↑	EC	<	TC	PC	>	SC	↑	EC	<	TC	PC	>	SC
2013–2014	↑	EC	<	TC	PC	>	SC	↑	EC	<	TC	PC	>	SC
2014–2015	↓	EC	<	TC	PC	<	SC	↓	EC	>	TC	PC	<	SC
2015–2016	↑	EC	>	TC	PC	>	SC	↑	EC	<	TC	PC	>	SC
2016–2017	↑	EC	>	TC	PC	<	SC	↑	EC	<	TC	PC	>	SC
2017–2018	↑	EC	<	TC	PC	>	SC	↑	EC	<	TC	PC	>	SC
2018–2019	↑	EC	>	TC	PC	<	SC	↑	EC	>	TC	PC	>	SC
1995–2019	↑	EC	<	TC	PC	>	SC	↑	EC	<	TC	PC	>	SC

Similarly, the adoption of RES has a comparable pathway for EU, as the greatest progress has been observed in Western (29.11%) followed by Northern (13.38%), Southern (–4.35%), and Central-Eastern EU (–9.23%). Overall, the adoption of RES has led to a European-level 7% amelioration from 1995 to 2019, meaning a 10-times greater productivity changes in comparison to NRES, a seemingly significant pathway towards green economy and carbon neutrality.

A further juxtaposition between NRES and RES is presented in Table 3, which depicts the general comparison between these two indices. At first glance, during the whole period of 1995–2019 the MLPI of NRES and RES have 16 and 17 performances above unity respectively, making the electricity generation from RES a bit more important for the TFP performance. Possibly because the technological changes have further expanded innovation on production technology in the EU-27.

By providing more detail, in the NRES MLPI there are 18 periods where technological change surpasses the efficiency changes. Although, the efficiency change is also affected mainly pure efficiency change (18 periods) and then by the scale changes (9 periods). Additionally, there are 19 periods when technological change plays a more important role than efficiency change in the RES MLPI. Even more, the efficiency change is affected and at this model primarily by pure efficiency change (18 periods) followed by scale changes (9 periods).

In essence, the results from Table 3 can be interpreted as that there are more shifts in the technology frontier due to technological change through the form of innovation rather than catch-up actions from efficiency changes. Moreover the number of pure efficiency changes showcases that there are more improvements in the core efficiency rather than returns-to-scale from the scale changes.

4 Discussion

Paving the way for carbon neutrality is being strengthened by solar and wind energy due to high energy return on investment (EROI)[9] (Stern 2020), as well as by advancements in LNG technology (Da Pan et al. 2020; Song et al. 2020; Balcombe et al. 2021). In Table 4 there are several discussed issues for RES and NRES accordingly. Solar and wind energy forms are of the most importance as they are well-established and well-rounded technologies among the RES. Whereas the NG and specifically LNG are going to be discussed based on NRES factor due to its significance in transportation and shipping.

Referring to solar energy the PVs illustrate plenty potentials for enabling rapid energy conversion from sunlight to electricity (Halkos and Gkampoura 2020), even for un-electrified developing countries (Ellabban et al. 2014). However, there is some controversy for the uncertain – variable or intermittent – operation, and life cycle emissions for PVs (Denholm et al. 2010; Mac Kinnon et al. 2018).

Another matter of discussion is the employment of auxiliary storage and backup systems for CSP systems, as well facing with GHGs emissions during the infrastructure installation and operation of such systems (Denholm et al. 2010; Ellabban et al. 2014; Mac Kinnon et al. 2018). Solar heating could also provide meaningful way-out of energy insecurity, as it can ameliorate modern lifestyles through the exploitation of the heating energy from the sun (Ellabban et al. 2014).

In parallel, wind energy infrastructure ought to be strengthened by auxiliary systems and regulatory incentives except the high-cost disincentives due to dangers towards avian wildlife (Denholm et al. 2010; Ellabban et al. 2014). On contrary, regarding the wind energy improvements there is no pollution in water and air as well (Ellabban et al. 2014), and it is explicitly advantageous for rural communities (Mac Kinnon et al. 2018; Halkos and Gkampoura 2020).

The transition towards a carbon neutral society and economy can be fostered or frustrated by driving forces. For instance, in EU incentives and disincentives are central for estimating the cumulative impact of NG or LNG on this transition. To exemplify, factors that hamper NG are the EU directives on GHGs commitments and the price volatility; whereas factors that boost are based on plethora of port growth opportunities and state-of-the-art LNG engine design against other conventional fossil fuel engines (Thomson et al. 2015).

Moreover, IMO has provided versatile and typically achievable targets, as the GHGs can be halved by 2050 on the shipping sector. Further, IMO has targeted the NOx and SOx (Lindstad and Rialland 2020) – a very purposeful action for combating air pollution and

[9] Stern stated that it is ''the ratio of useful energy produced by an energy supply system to the amount of energy invested in extracting that energy (Stern 2020).

Table 4 Issues on green energy forms

Forms of Green Energy		Impact	References
RES			
Solar	PVs	Variable and uncertain output	Denholm et al. 2010
		Efficient even with mere sunlight, allowing for economies of scale, and can be utilized in un-electrified developing countries	Ellabban et al. 2014
		Life cycle emissions for PVs are considered among the highest for R.E.S. but excessively below any kind of coal or N.G. emissions	Mac Kinnon et al. 2018
		Fast conversion of sunlight into electricity	Halkos and Gkampoura 2020
	CSP	Utilization of high-efficiency TES, but less efficient when there is no sunlight or ramping events	Denholm et al. 2010
		Required storage and backup systems	Ellabban et al. 2014
		Life cycle GHG emissions due to plant design	Mac Kinnon et al. 2018
	Solar Heating	Effective for contemporary amenities	Ellabban et al. 2014
Wind	Wind turbines	Increased costs due to frequency regulation, load following, and wind uncertainty (scheduling cost)	Denholm et al. 2010
		Free source of energy with no water or GHG emissions, but detrimental for avian wildlife	Ellabban et al. 2014
		Wind power needs auxiliary infrastructure for power storage and dispatchable technologies for exploiting larger wind penetration	Mac Kinnon et al. 2018
		Beneficial for rural areas, leading to prosperity the local populations	Halkos and Gkampoura 2020
NRES			
LNG		Methane slipping from engines is exorbitantly high, but the best-performing LNG engines can reduce global warming potential by about 30%	Balcombe et al. 2021
		VOC emissions form LNG-fueled vehicles are stressing urban air quality	Song et al. 2020
		Safe storage, transport, bunkering, and use is of alerting status	Elgohary et al., 2014
		Low criteria pollutant and GHGs emissions relatively to other fossil fuels and it has potential for transition to 100% renewable fuel	Mac Kinnon et al. 2018
		Fulfils I.M.O. air emission regulations due to low sulfur content and lower nitrogen oxide emission	Lindstad and Rialland 2020
		Competitiveness in maritime—global or regional-demand, meeting GHGs targets, and port growth but CH_4 emissions due to NG extraction and storage methods	Thomson et al. 2015

mitigating these emissions. In general, it is the whole competitiveness in maritime sector that ought to be fostered through proper regulatory incentives (Thomson et al. 2015).

Copying with climate change is in tandem with attaining carbon neutrality. Climate change is gaining momentum in Europe, especially in the Mediterranean basin: where climate change has profound effects on ecosystems (Ali et al. 2022; Bednar-Friedl et al. 2022). Rising resilience in the Mediterranean broader region and in Europe is unequivocally a hot issue (Schipper et al. 2022), hence carbon neutrality is also gaining political, economic, and social debates under the scope of climate change.

This is a reason why SDGs have offered a medium on promoting the fighting of climate change and on providing guidelines for carbon neutrality. On the whole, SDG 13 targets exclusively climate change, and SDG 7 primarily and SDGs 11, 12 indirectly call for clean and affordable energy and typically for carbon neutrality, resilience, and responsible consumption patterns (UN 2016; Fotopoulou et al. 2022).

To recapitulate, both NRES and RES are part and parcel of the modern energy economics. Specifically when targeting the realization of carbon neutrality objectives. Both of the above energy sources can typically lead to a more clean and sustainable economies and communities. SDGs can be also possible resolution on promoting carbon neutrality.

5 Conclusions and Policy Implications

To recapitulate, either NRES as the discussed—and important transitional fuel—LNG, or the all-around and fully developed RES as the solar and wind energy systems should be taken into account when trying to realize carbon neutrality commitments. Communities and societies can be ushered to more clean and sustainable future through carbon neutrality. A probable answer is the successful conclusion of SDGs (e.g., SDGs 13, 7, 11, and 12) on energy economics via the copying of warfare effects on global or regional economies and energy instability cycles. In parallel, the EGD could be described as a global pathfinder regarding the provision of robust regulatory framework for posing impediments on further climate change and bolstering carbon neutrality.

Furthermore, the two measured productivity indices showed that the adoption of RES ushered to greater performance, even if CO_2 and CH_4 have a powerful impact on TFP. More specifically, the average MLPI of NRES and RES is 2.14% and 7.14% respectively. Regarding the geographical categorization, for both models, the greater performance is attributed to Western EU followed by Northern, Southern, and Central-Eastern EU. Significant is to propose that the Southern and Central-Eastern EU countries ought to expand further their RES technologies in order to ameliorate their productivity performance. Some ways, as discussed above, are the installation of more PVs or wind farms, aiming to grasp their potential in the rising energy markets.

Some policy implications can be targeted on the issues of energy sources diversification, on resource conservation, and the alleviation of energy poverty. The diversification of energy sources would enable to grasp the dynamic potential of RES, moreover this diversification would complement the governmental action on resource conservation, as RES need less natural resources than NRES. The most important, however, is the impact to the society and the adoption of RES would allow more access to affordable electricity and energy security. In essence, RES can be a helping hand for the alleviation of energy poverty in EU, this phenomenon might also help other third countries.

To put it briefly, SDGs can provide useful guidance on dealing with climate change through carbon neutral promotion. The current energy crisis provokes phenomena like energy poverty and economic fragility and volatility. Hence the introduction of resilience in economic, societal, and environmental terms is of great importance. Above all, carbon neutrality might open the way for copying climate change—in short, it is a matter of survival and the base of a clean and sustainable world-to-come.

Appendix 1

See Table 5.

Table 5 Efficiency change of the NRES and RES

DMU	NRES		RES	
	1995–1996	2018–2019	1995–1996	2018–2019
AUS	1.0000	1.0657	0.8900*	1.0609
BEL	0.9746	1.0662	1.0000	1.0662
BUL	1.1730	0.9662	1.0391	0.9890
CRO	1.0000	1.0251	0.9769	0.9826
CYP	1.0622*	1.0490	1.0000	1.0826
CZE	1.0249	1.0392	0.9852	1.0423
DEN	0.9802	1.0000	0.9802	1.0000
FIN	0.9408*	1.1164	0.9408*	1.1164
FRA	1.0000	1.0073	1.0000	1.0079
GER	0.9831	1.0922	1.0000	1.0922
GRE	0.9958	1.0000	0.9858	1.0000
HUN	1.0270	0.9471	0.9230*	0.9993
IRE	0.9493	1.0000	0.9437	1.0000
ITA	1.0000	1.0712	1.0000	1.0712
LAT	1.0000	1.0674	0.8298*	1.0313
LIT	0.9809	1.0686	0.9743	1.0497
LUX	1.0000	1.0000	1.0000	1.0000
MAL	0.9693	1.0000	1.0000	1.0000
NTH	0.9585	1.0618	1.0000	1.0472
POL	1.0202	1.0078	0.9351	1.0542
POR	1.0180	1.0672	1.0317	1.0545
ROM	0.9832	0.9974	0.7499*	0.9676
SLK	0.8701*	1.0094	0.8365*	0.9908
SLN	1.0135	1.0399	1.0131	1.0399
SPA	1.0166	1.0552	1.0143	1.0552
SWE	1.0000	1.0000	1.0000	1.0000
UK	1.0000	1.0721	1.0000	1.0721
Mean	0.9978	1.0331	0.9648	1.0323
N. EU mean	0.9785	1.0541	0.9481	1.0449
W. EU mean	0.9852	1.0419	0.9815	1.0392
C&E EU Mean	1.0141	0.9989	0.9208	1.0037
S. EU Mean	1.0108	1.0404	1.0064	1.0433

The (*) denotes that there is statistically significant difference via the bootstrap technique

Appendix 2

See Table 6.

Table 6 Technological change of NRES and RES

DMU	NRES		RES	
	1995–1996	2018–2019	1995–1996	2018–2019
AUS	0.6458*	0.8961	1.0546	0.9002
BEL	1.0251	0.9128	0.7719	0.9128
BUL	1.9105*	1.0431	1.9770*	1.0401
CRO	0.8373*	0.9340	0.8375*	0.9798
CYP	0.9829	0.9507	1.0099	0.9199
CZE	0.9718	0.9438	1.0045	0.9370
DEN	1.0073	1.3469	0.7295*	1.2110
FIN	1.0031	0.9093	1.0031	0.9093
FRA	0.9457	0.9674	0.5498*	0.9666
GER	1.0300	0.9050	0.5342*	0.9050
GRE	0.9702	1.0440	0.9774	1.0440
HUN	0.9334*	0.9758	1.0195	0.9183
IRE	0.9771	1.0266	0.9827	1.4724
ITA	1.0354	0.9209	1.0360	0.9210
LAT	0.8020*	0.9456	0.9701	0.9854
LIT	1.0109	0.9076	1.0317	0.9203
LUX	0.9114	0.9758	0.9359	0.9757*
MAL	0.9878	0.9584	0.9865	0.6427*
NTH	1.0115	0.9136	0.5526*	0.9151
POL	0.9112*	0.9937	0.9688	0.9523
POR	0.9931	0.9496	0.9582	0.9605
ROM	0.9402	0.9730	1.2583*	1.0093
SLK	0.9454*	0.9701	0.9821	0.9712
SLN	0.9577*	0.9547	0.9579	0.9547
SPA	0.9992	0.9362	0.9981	0.9362
SWE	1.0000	1.0129	1.0000	1.0129
UK	0.9801	0.9386	1.0052	0.9386
Mean	0.9899	0.9706	0.9664	0.9708
N. EU mean	0.9622	0.9567	0.9988	1.0398
W. EU mean	0.9395	0.9882	0.7327	0.9695
C&E EU mean	1.0643	0.9762	1.1497	0.9726
S. EU mean	0.9895	0.9592	0.9892	0.9113

The (*) denotes that there is statistically significant difference via the bootstrap technique

Appendix 3: The Simar and Wilson 1999 bootstrap

The idea of this bootstrap is the construction of the confidence intervals based on the assumption that the distribution of the difference between the real unknown index (M_S^I) and the estimated values $\widehat{M}_S^I$ of the index can be approximated by the distribution of the difference between the bootstrapped ($M_{S,b}^{*I}$) and the estimated values ($\widehat{M}_S^I$) of the index (Simar and Wilson 1999; Halkos and Tzeremes 2015). Hence, the confidence interval $(1-a)$ can be between the values b_a and a_a as below:

$$\Pr\left(b_{s,a} \leq \widehat{M}_S^I - M_S^I \leq a_{s,a}\right) = (1-a)$$

This nexus can be approximated from the values generated ($\widehat{b}_a and \widehat{a}_a$) through the bootstrap technique:

$$\Pr\left(\widehat{b}_{s,a} \leq M_{S,b}^{*I} - \widehat{M}_S^I \leq \widehat{a}_{s,a}\right) = (1-a)$$

Therefore, the bootstrap estimate of the MPI or MLPI or their components can be given as:

$$\widehat{M}_S^I - \widehat{a}_{s,a} \leq M_S^I \leq \widehat{M}_S^I - \widehat{b}_{s,a}$$

As a result, the s th DMU (on the present study one of the 27 countries) the 1 MLPI is statistically different from unity at a per cent level if the last equation does not include the value 1. According to Simar and Wilson, a proper B = 2000 replications are needed, or B = 1000 as Hall suggested (Hall 1986; Simar and Wilson 1998).

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Declarations

Conflict of interest The authors declare no conflict of interest.

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