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Economic, Environmental, and Energy Equity Convergence: Evidence of a Multi-Speed Europe?

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Abstract

The European Union has committed to make Europe the first climate-neutral continent by 2050. Reaching this objective implies massive changes in the economies of the region. The biggest challenge of this green transition is to make sure that it happens without sacrificing economic progress and guaranteeing justice and inclusiveness. This pledge requires that every country be capable of addressing the trade-offs between the targets while remaining committed towards the common decarbonisation goal. This paper analyses the success with which European countries are carrying out the energy transition. We propose an enhanced hyperbolic distance function and a stochastic frontier analysis approach to model the joint attainment of economic development, environmental sustainability, and energy equity. We apply our model to an unbalanced panel dataset of 29 European countries for the period 2005-2018. Our estimates show that the average performance of the European economies has improved throughout the studied period. However, the patterns of progress have been different, showing the non-EU-15 countries a steeper evolution than the EU-15 countries. Our results also highlight the pivotal role of a sustainable economic development with clean energies for both slashing CO_2 emissions and fostering energy equity. Moreover, we find sigma convergence, being this slightly higher for the EU-15 countries. Additionally, we obtain absolute and conditional beta convergence for both non-EU-15 and EU-15 countries. Finally, we show that a higher share of renewable energy sources helps countries that are lagging behind to reach their optimal level of performance.

Keywords: economic development; environmental sustainability; energy equity; enhanced hyperbolic distance function; stochastic frontier analysis.

JEL classification: C5, L5, L9, Q4, Q5.

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1. Introduction

Current economies are increasingly complex, interlinked, and have to adapt to a continuously evolving global environment. Some recent examples of this changing context are the COVID-19 pandemic, the 2022 Russian invasion of Ukraine, and the rising frequency of extreme weather events worldwide. All these challenges put a strain on countries and call for a constant technological progress that implies redevising new, more efficient, competitive, and environmentally sustainable production models. These objectives join other traditional ones such as the reduction of inequality and poverty.

However, these objectives might not be mutually exclusive. Since the 1990s, diverse empirical analyses have examined whether there exists an inverted U-shaped relationship between various environmental degradation indicators and economic growth (Shahbaz and Sinha, 2019; Awaworyi Churchill et al., 2018; Balado-Naves et al., 2018; Stern, 2017; Grossman and Krueger, 1991). This hypothesis is generally known as the Environmental Kuznets Curve (EKC) and, if held, it may imply that increasing levels of income naturally lead to environmental quality improvements.

Regardless of this, the objectives of the Paris Agreement are still far from being achieved. After the 2020 global lockdown due to the COVID-19 pandemic, the level of CO_2 emissions linked to energy combustion and industrial processes rebounded and peaked at the highest level of annual emissions in history (IEA, 2022). This resulted in a new record in the atmospheric levels of the three main greenhouse gases (GHG) (i.e., carbon dioxide, methane, and nitrous oxide) in 2021 (WMO, 2022).

Cutting the level of emissions and achieving a low-carbon future is usually linked to technological progress derived from innovation in renewable energy development (Castrejon-Campos et al., 2022). In addition, the electrification of the economy, energy demand reductions (via, e.g., energy efficiency improvements), and a more flexible and integrated energy system are also frequently suggested as potential solutions to reach the decarbonisation goals. In particular, the proposition of an integrated energy system that takes advantage of synergies within and between sectors may provide efficiency gains and lead to a clean, affordable, and secure energy system (Cambini et al., 2020; Jamasb and Llorca, 2019). Furthermore, the green transition from using polluting energy sources to clean ones may offer opportunities to reduce inequality among citizens via fiscal policies. For example, the revenues derived from taxes levied on emissions may be reinvested in aid to the most vulnerable individuals and households as a potential redistributive measure to counteract inequality (Fremstad and Paul, 2019; Boyce, 2018).

In recent years, the European Union (EU) has proposed diverse measures to meet these economic, environmental, and equity goals. Some examples are the 2030 Agenda, which includes various Sustainable Development Goals (SDGs) intended to eradicate poverty and achieve a more sustainable world;[1] the European Green Deal,[2] which comprises a series of policies to reach the objective of making Europe the first climate-neutral continent by 2050;[3] or the allocation of a significant contribution of resources through the EU's recovery plan after the COVID-19 pandemic, namely NextGenerationEU.[4] This economic recovery package requires that at least 37% of every Recovery and Resilience Facility national plan is earmarked for climate change-related projects. Recently, with the 'Fit for 55' package proposed in July 2021,[5] the EU seeks to reduce net emissions by at least 55% in 2030 compared to 1990 and establish a transitional step before climate neutrality is achieved by 2050. Specifically, the 'Fit for 55' package is a set of proposals that seeks to guarantee a fair, competitive, and ecological transition.

These goals are closely related to what is known in the literature as the 'energy trilemma' (World Energy Council, 2022), which represents three potentially conflicting dimensions: *Energy security*, which means guaranteeing the ability of an economy to meet energy demand; *Energy equity*, which is concerned with the capacity to ensure that the energy supply is affordable for the entire population; and *Environmental sustainability*, which seeks the provision of resources and services needs for the current and future generations without compromising the ability of the ecosystems to continue providing them. It can be argued that the objectives of the green transition are designed to maintain a balance among the three dimensions of the energy trilemma. In fact, this was emphasised when the Council of the European Union declared that the transition towards climate neutrality has to be 'fair and inclusive.'[6]

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[1] https://ec.europa.eu/info/strategy/international-strategies/sustainable-development-goals_en.
[2] https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6691.
[3] The Green Deal can be seen as a continuation of the EU Clean Energy for all Europeans Package (CEP) that included eight new legislative texts and covered five key dimensions: energy security, the establishment of a fully integrated internal energy market, energy efficiency, the decarbonisation of the economy, and the promotion of research, innovation, and competitiveness (Nouicer et al., 2021).
[4] https://ec.europa.eu/info/strategy/recovery-plan-europe_en.
[5] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0550.
[6] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=uriserv:OJ.C_.2022.243.01.0035.01.ENG.

This paper analyses the success with which European countries are carrying out an efficient green transition. We propose to estimate an enhanced hyperbolic distance function that facilitates modelling the simultaneous production of both good and bad outputs and allows us to calculate Environmental technical Efficiency (EE) indices. These indices take into account three aspects: i) energy poverty, which reflects to what extent the energy transition guarantees the availability of energy services to all the citizens; ii) economic development, measured by GDP; and (iii) environmental sustainability, proxied via CO_2 emissions.

In addition, adopting the convergence models of traditional neoclassical theory, we analyse whether this green transition is homogeneous across the European countries. The concept of traditional convergence occurs when countries' income growth rates are negatively associated with their initial levels. The starting hypothesis is that poor economies tend to grow faster than rich ones (Baumol, 1986; Barro, 1991; Barro and Sala-i-Martin, 1992). In our paper we study whether the countries that start with worse EE indices evolve at a higher rate than those that start with higher EE indices. In other words, we carry out an empirical analysis to test the existence of convergence in the energy transition process.

The structure of the paper is as follows. Section 2 provides a brief review of the literature related to the objectives of this study and the methodology applied. Section 3 describes the methodology that will be used and the empirical specification of the model that will be estimated. Section 4 presents the data used in the analysis and their sources. Section 5 reports parameter estimates and main results. Section 6 shows the main conclusions and policy implications.

2. Literature Review

It is possible to analyse the techno-economic and environmental performance of a sector by jointly modelling the production of desirable (e.g., electricity generation) and undesirable outputs (e.g., GHG emissions attached to electricity generation). Directional and hyperbolic distance functions have been developed in the literature to empirically study the efficiency of firms in maximising the 'good' outputs and minimising the 'bad' ones. In their seminal paper, Färe et al. (1989) propose the application of Data Envelopment Analysis (DEA) (i.e., a nonparametric technique) to measure hyperbolic efficiency as an alternative to the multilateral productivity indices introduced by Pittman (1981). They applied the methodology to a sample of 30 paper-producing mills operating in the US in 1976 to illustrate the proposed approach.

Since then, directional and hyperbolic distance functions have occasionally been used to study the operation of utilities in the energy sector. Färe et al. (2005) estimate a directional distance function (using both nonparametric and parametric techniques) to examine the technical efficiency of US electric utilities that produce electricity and a polluting by-product, SO_2. Cuesta et al. (2009) introduced a new procedure to estimate a translog hyperbolic distance function applying a parametric approach, namely Stochastic Frontier Analysis (SFA). By doing so, it is possible to examine the economic characteristics of the underlying technology in a sector. They use this model to evaluate the environmental technical efficiency of utilities using a sample based on the one provided by Färe et al. (2005). The outputs of the utilities are also electricity and SO_2 emissions, while they use as inputs generating capacity, fuel, and labour. They compare different distance function specifications (output-oriented, hyperbolic, and enhanced hyperbolic) and show that translog hyperbolic and enhanced hyperbolic distance functions can be implemented within an SFA framework and easily estimated using standard econometric techniques.

There is also a small number of papers that look into the economic and environmental performance of energy sectors at macroeconomic level. Corsatea and Giaccaria (2018) explore the productivity and the environmental technical efficiency of electricity and gas sectors in 13 EU countries. They employ the parametric hyperbolic distance function developed by Cuesta and Zofío (2005) and Cuesta et al. (2009). They consider two outputs – the value added (good output) and CO_2 emissions (bad output) – and two inputs (capital and labour), in addition to information about energy market reforms that occurred in the EU between 1995 and 2013. They find that regulation fostering privatisation and the removal of entry barriers had a positive impact on the competitiveness and environmental sustainability of the sectors studied. Moreover, they also find that, on average, these sectors still have potential to increase their value added (by 5.9%) while simultaneously reducing their CO_2 emissions (by 5.6%).

Zhang and Ye (2015) analyse the environmental efficiency of a panel dataset of 29 provinces in China from 1995 to 2010. They consider two outputs (GDP and SO_2 emissions) and three inputs (capital, labour, and energy). They decompose the growth of environmental total factor productivity into environmental technical change and environmental efficiency change. They find that China also has potential for reducing SO_2 emissions and simultaneously increase GDP. However, they find large discrepancies in environmental efficiencies across the provinces and regions of the country.

There are also studies that have carried out convergence analyses of environmental impact in the energy sector. For example, Duman and Kasman (2018) examine environmental technical efficiency for a sample of European countries during the period 1990-2011 using a parametric enhanced hyperbolic distance function.[7] They consider two outputs (GDP and CO_2 emissions) and three inputs (capital, labour, and energy). They find that EU-15 countries have a greater potential for simultaneously reducing CO_2 emissions and increasing GDP than new members and the candidate countries. They also consider environmental technical efficiency convergence among EU countries. Their results show that both absolute beta convergence and sigma convergence exist among the EU countries.

Balado-Naves et al. (2023) propose a model to carry out a convergence analysis in terms of energy intensity levels as a way of approximating for energy efficiency.[8] There is evidence in the literature that energy intensity convergence drives energy consumption convergence for OECD countries.[9] These authors estimate several spatial econometric models for 153 countries between 1999 and 2018. In general terms, they find worldwide convergence conditional to the spatial distribution of countries and diverse economic features such as capital accumulation, total factor productivity growth, the share of renewable energy sources in the energy mix, and population growth.

Our paper contributes to the previous literature in two ways. First, we extend the analysis of the sustainability of the economy by considering energy equity as an additional target to economic development and environmental sustainability, thereby completing our own 'energy trilemma.' By estimating an enhanced hyperbolic distance function that fulfils the theoretical properties required by the theory, it is possible to obtain information of the underlying production technology allowing us to reveal how economies have evolved in terms of a fairer, more competitive, and environmentally friendly transition. Second, we

[7] However, it must be noted that the enhanced hyperbolic distance function estimated by those authors does not satisfy the theoretical properties of such a type of function because it does not comply with the monotonicity conditions.
[8] It is recognised that the use of energy intensity as a proxy for energy efficiency may yield unreliable results (IEA, 2014). However, the difficulty in the measurement of energy efficiency, makes common the use of energy intensity indicators as a substitute for different sectors such as transport (Llorca et al., 2017).
[9] See Balado-Naves et al. (2023) for a good review of the literature on this topic.

expand the evaluation of the environmental efficiency convergence by including absolute beta convergence and distinguishing between EU-15 and other European countries. This allows us to test whether the current European green energy transition is happening at a homogeneous pace or, on the contrary, the economies advance in this transition at different rhythms, i.e., we have a multi-speed Europe.

3. Methodology

3.1. Enhanced Hyperbolic Distance Function

Following Cuesta et al. (2009), the enhanced hyperbolic distance function is defined as:

$$D_E(x, v, w) = \inf\{\phi > 0 : (x\phi, v/\phi, w\phi) \in T\} \tag{1}$$

where x is the input vector $(x_1,\ldots,x_K)$; v stands for the vector of desirable outputs $(v_1,\ldots,v_M)$, w represents the undesirable output, T is the production possibility set, and $\phi > 0$.[10] The enhanced hyperbolic distance function (D_E) represents the maximum feasible and simultaneous increase of desirable outputs and reduction of inputs and undesirable outputs, given the technology. D_E ranges between 0 and 1. If it equals one, there is full environmental technical efficiency, which means that it is not possible to augment desirable outputs and shrink inputs and bad outputs simultaneously beyond the current levels.

Theoretically, the enhanced hyperbolic distance function must fulfil the following properties: i) nondecreasing in desirable outputs, ii) nonincreasing in inputs, iii) nonincreasing in undesirable outputs, iv) dual of the profitability function and v) almost homogeneous of degrees (–1,1,–1,1), which implies that:

$$\mu D_E = D_E(\mu^{-1}x, \mu v, \mu^{-1}w), \qquad \text{for any } \mu > 0 \tag{2}$$

If we chose the inverse of the M^{th} output as μ, i.e., $\mu = 1/v_M$, taking natural logarithms and rearranging Equation (2), we obtain:

$$-\ln v_M = \ln D_E \left(v_M x, \frac{1}{v_M} v, v_M w\right) - \ln D_E \tag{3}$$

Changing the notation of $-\ln D_E$ to u, which represents the environmental technical inefficiency, we have:

[10] The parameter ϕ is simply a positive scalar that makes possible the expansion of the desirable outputs (v) and the contraction of undesirable outputs (w) and inputs (x).

$$-\ln v_M = \ln D_E \left(v_M x, \frac{1}{v_M} v, v_M w\right) + u \quad (4)$$

Regarding the functional form, we specify a translog function. Moreover, to estimate the enhanced hyperbolic distance function it is necessary to impose the almost homogeneity conditions (Coelli and Perelman, 1999; Cuesta et al. 2009) as follows:[11]

$$\begin{aligned} -\ln v_{Mit} = {} & \alpha_i + \sum_{k=1}^{K} \alpha_k \ln x_{kit}^* + \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \alpha_{kl} \ln x_{kit}^* \ln x_{lit}^* + \sum_{m=1}^{M-1} \beta_m \ln v_{mit}^* \\ & + \frac{1}{2}\sum_{m=1}^{M-1}\sum_{n=1}^{M-1} \beta_{mn} \ln v_{mit}^* \ln v_{nit}^* + \chi_w \ln w_{it}^* + \frac{1}{2}\chi_{ww}(\ln w_{it}^*)^2 \\ & + \sum_{k=1}^{K}\sum_{m=1}^{M-1} \delta_{km} \ln x_{kit}^* \ln v_{mit}^* + \sum_{k=1}^{K} \varsigma_{kw} \ln x_{kit}^* \ln w_{it}^* \\ & + \sum_{m=1}^{M-1} \Psi_{mw} \ln v_{mit}^* \ln w_{it}^* + \gamma_t t + \frac{1}{2}\gamma_{tt} t^2 + \sum_{k=1}^{K} \gamma_{kt} \ln x_{kit}^* \, t \\ & + \sum_{m=1}^{M-1} \gamma_{mt} \ln v_{mit}^* \, t + \gamma_{wt} \ln w_{it}^* \, t + u_{it} + \varpi_{it} \end{aligned} \quad (5)$$

where i stands for the i^{th} country, while $v_{mit}^* = v_{mit}/v_{Mit}$, $w_{it}^* = w_{it} v_{Mit}$, and $x_{kit}^* = x_{kit} v_{Mit}$. In addition, α, β, χ, δ, ζ, Ψ, and γ represent parameters to be estimated. We include a time trend ($t = 1,\ldots,T$) to capture technological progress. Moreover, the term u, already displayed in Equation (4), is assumed to follow a half-normal distribution and, as mentioned above, represents the environmental technical inefficiency. Finally, ϖ is a standard random noise term that follows a normal distribution.

According to Kumbhakar and Lovell (2000), ignoring heteroscedasticity in the composed error term may lead to biased estimates. In modelling determinants of inefficiency by means of the vector z($z_1,\ldots,z_N$), Wang and Schmidt (2002) proposed a strategy in which the random variable representing inefficiency has the following form:

$$u_{it} \sim h(z_{it}, \lambda) u_{it}^* = h_{it}\, u_{it}^* \quad (6)$$

[11] Note that inputs and outputs appear in ratio form. In this way, the ratio of these variables could be considered as exogenous variables. In other words, by imposing almost homogeneity conditions, we can obtain consistent estimates (for details, see Coelli, 2000; or Kumbhakar, 2011).

On the one hand, $h_{it} = h(z_{it}, \lambda) \geq 0$ (scaling function) is an observation-specific non-stochastic function of the exogenous variables (heteroscedastic term). On the other hand, u_{it}^{*}, that does not depend on z_{it}, is common to all observations (homoscedastic term). Finally, λ represents an additional set of parameters to be estimated. From Equations (4-6) we define the environmental technical efficiency scores as follows:

$$EE_{it} = \exp(-u_{it}) \tag{7}$$

This means that once the enhanced hyperbolic distance function has been estimated, it is possible to obtain the EE indices. Moreover, we can deduce useful characteristics of the technology such as the level of substitutability and complementarity between inputs and outputs.

3.2. Measuring Substitutability and Complementarity of Outputs

The enhanced hyperbolic distance function may be used to obtain measures of substitutability and complementarity between outputs. Starting from the definition of the enhanced hyperbolic distance function and taking into account that along the frontier $D_E(x,v,w)$ remains unchanged, the differential of this function will be:

$$dD_E = \frac{\partial D_E}{\partial x}dx + \frac{\partial D_E}{\partial v}dv + \frac{\partial D_E}{\partial w}dw = 0 \tag{8}$$

Moreover, considering that along the frontier the inputs remain unchanged, we get that:

$$\frac{\partial D_E}{\partial v}dv = -\frac{\partial D_E}{\partial w}dw \rightarrow \frac{dv}{dw} = -\frac{\frac{\partial D_E}{\partial w}}{\frac{\partial D_E}{\partial v}} \tag{9}$$

where $\frac{\frac{\partial D_E}{\partial w}}{\frac{\partial D_E}{\partial v}} = MRT$ is the Marginal Rate of Transformation between a desirable output v and the undesirable output w along the frontier, i.e., the MRT is the slope of the Production Possibility Frontier (PPT). In this way, the MRT can be interpreted as the shadow price of the undesirable output in terms of the desirable one (Grosskopf et al., 1995).

In a similar way, from Equation (8), and considering two arbitrary desirable outputs m and n, we have the Marginal Rate of Transformation between the two outputs along the frontier as follows:

$$\frac{dv_n}{dv_m} = \frac{\frac{\partial D_E}{\partial v_m}}{\frac{\partial D_E}{\partial v_n}} \quad (10)$$

In this case, the MRT can also be interpreted as the ratio of shadow valuation of the outputs. Due to the logarithmic form of the translog specification in Equation (5), Equation (10) can be defined in elasticity terms as:

$$\frac{\frac{\partial D_E}{\partial v_m}}{\frac{\partial D_E}{\partial v_n}} = \left(\frac{\frac{\partial \ln D_E}{\partial \ln v_m}}{\frac{\partial \ln D_E}{\partial \ln v_n}}\right)\left(\frac{v_m}{v_n}\right) = \left(\frac{\varepsilon_{D,v_m}}{\varepsilon_{D,v_n}}\right)\left(\frac{v_m}{v_n}\right) \quad (11)$$

In Equation (11), the MRT varies with the changes of the ratio of outputs because increased production of one output alone occurs at a higher opportunity cost. Thus, a more interpretable indicator of substitutability can be defined in terms of relative rather than absolute values by normalising the MRT with the output ratio (Grosskopf et al., 1995), obtaining:

$$Subs_{v_m,v_n} = \frac{\varepsilon_{D,v_m}}{\varepsilon_{D,v_n}} \quad (12)$$

High values of $Subs_{v_m,v_n}$ (i.e., greater than one) indicate difficulty (high opportunity cost) in the substitution between v_m and v_n, which in turn implies relative complementariness, and vice versa.

Similarly, considering Equation (9) in terms of w and v_m, taking logs, and normalising, we can define:[12]

$$Subs_{v_m,w} = -\frac{\varepsilon_{D,v_m}}{\varepsilon_{D,w}} \quad (13)$$

As we described before, Equation (13) indicates the relative opportunity cost of the output v_m (desirable) in terms of the output w (undesirable).[13] High values of $Subs_{v_m,w}$ indicate a high opportunity cost of v_m in terms of w, showing low substitutability between them.

[12] Where: $MRT = \frac{\frac{\partial D_E}{\partial v_m}}{\frac{\partial D_E}{\partial w}} = \left(\frac{\frac{\partial \ln D_E}{\partial \ln v_m}}{\frac{\partial \ln D_E}{\partial \ln w}}\right)\left(\frac{w}{v_m}\right) = \left(\frac{\varepsilon_{D,v_m}}{\varepsilon_{D,w}}\right)\left(\frac{w}{v_m}\right)$.

[13] We add a negative sign to facilitate the interpretation.

3.3. Beta and Sigma Convergence

As mentioned previously, in this paper we adopt the idea of neoclassical convergence to analyse, in an empirical exercise, whether the environmental efficiency of the different countries follows an evolution compatible with the traditional principle of convergence. The underlying idea of this analysis is that given the objective of achieving a fair, competitive, and ecological energy transition, countries must be efficient in guaranteeing economic growth and energy equity while minimising CO_2 emissions. The optimal level of efficiency would be the equivalent in this context to the steady state.[14]

Traditionally, convergence has been analysed through two concepts: absolute and conditional beta (β) convergence, and sigma (σ) convergence. The equation that we will use to estimate the β-convergence can be written as follows:

$$\frac{\ln\left(\frac{EE_{iT}}{EE_{i0}}\right)}{T} = a + b \ln EE_{i0} + \sum_{r=1}^{R} \partial_r q_i + \varepsilon_i \qquad (14)$$

where i stands again for the i^{th} country, T is the number of years of the sample, a is the intercept, b represents the parameter that identifies the effect of the initial level of EE on the average growth rate for the period T, q is a vector of R variables associated to conditional convergence factors, ∂ are the parameters linked to the variables of the q vector, and ε_i is the noise term. There is β-convergence between the economies when the parameter b exhibits a negative and significant value. This means that the growth rate of the EE index and the value of the index for the first year of the sample, have a negative correlation, or, in other words, countries with a lower level of initial EE show greater increases in efficiency over the sample period. In addition, a larger value of b in absolute value implies a stronger tendency to converge. Finally, it is possible to calculate the rate – or speed – of convergence as follows:

$$\beta = -\frac{\ln(1-b)}{T} \qquad (15)$$

However, the concept of absolute β-convergence implies that the technology is the same for every economy, so that the equilibrium is common to all of them. In this study we also analyse conditional β-convergence, which implies the possibility of different optimal EE levels depending on the conditions of each economy (Barro and Sala-i-Martin, 1992). In this sense, in the vector q of Equation (14) we will include the same variables that are

[14] According to the traditional macroeconomic growth models, the steady state represents the long-run equilibrium between production and population growth in an economic system.

significant as determinants of the environmental technical inefficiency under the assumption that they can also affect the conditional beta convergence.

Sigma convergence is based on the hypothesis that, if there is convergence, the dispersion of the distribution of the EE indices must decay as time goes by. It is therefore expected that the differences in efficiency between different economies or regions decrease over time. In other words, sigma convergence tests whether there is a reduction in the disparities between the different countries. The most commonly used measures of sigma convergence are the standard deviation and the coefficient of variation. Specifically, in our analysis we will use the coefficient of variation, which is a normalised measure of dispersion and is defined as the ratio of the standard deviation to the mean.

4. Data

In our sample, we have included European countries that have data available for the variables included in the model. We obtain an unbalanced panel dataset of 398 observations with 29 countries observed from 2005 to 2018. The EU-15 countries are: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the United Kingdom. The rest of the European countries included in our sample are: Bulgaria, Croatia, Cyprus, Czechia, Estonia, Hungary, Latvia, Lithuania, Malta, Norway, Poland, Romania, Slovakia, and Slovenia.

All the data used in this paper have been obtained from Eurostat except the variable representing CO_2 emissions, which has been obtained from BP's database[15] and capital stock, obtained from the Penn World Table (Feenstra et al., 2015). We consider three outputs. Two of them are desirable outputs: economic development (measured as GDP) and energy equity, *E_EQ* (measured as the percentage of people who do not live in an 'energy poverty' situation[16]). The third one is an undesirable output, and it is defined by the CO_2 emissions of each country. We include three inputs as factors of production in

[15] https://www.bp.com.

[16] Energy equity "assesses a country's ability to provide universal access to affordable, fairly priced and abundant energy for domestic and commercial use" (World Energy Council, 2022, p.5). The term energy equity is often used interchangeably with 'energy affordability,' which is linked with the concept of energy poverty. Energy poverty represents a social policy issue that refers to households that cannot afford to keep their houses warm nor fulfil other energy needs to meet minimum standards of health and wellbeing (Rodriguez-Alvarez et al., 2021; Llorca et al., 2020; Boardman, 1991). In our paper, energy poverty is defined as the inability to keep the home adequately warm. This information is included in the EU Statistics on Income and Living Conditions (EU-SILC).

the economy: labour (*L*), capital (*K*), and energy (*E*). As control variables, we consider the effect on the technology of the ratio of utilisation of renewable to total energy sources in electricity production (*SH_RES*), population (*POP*), a Gini coefficient (*GINI*) to capture other types of inequality, and a dummy variable that indicates whether the countries are net importers (*IMPORTER*) or net exporters of energy.[17] We also add the dummy variable *CRISIS* to control for the impact of the 2007-2008 economic crisis.

As inefficiency determinants, we additionally incorporate the renewable energy utilisation ratio (*SH_RES*), the Gini coefficient (*GINI*), and a trend variable (*t*). Finally, we also include a dummy variable (*EU-15*) that takes value 1 if the country belongs to EU-15 and zero otherwise.

Table 1 shows a brief description of the data, while Table 2 presents the summary statistics of the variables. *GDP* has been deflated using the Harmonised Index of Consumer Prices HICP (base 2015 = 100) obtained from Eurostat.

Table 1. Data description

Variable	***Description***	***Units***
GDP	GDP at market prices	Chain linked volumes (2010), million euro
CO2	Carbon dioxide emissions	Million tonnes
E_EQ	Energy equity (people not in energy poverty)	Percentage
L	Active population (from 15 to 64 years)	Thousand people
K	Capital stock	Constant 2017 USD
E	Gross inland energy consumption	Thousand tonnes of oil equivalent (toe)
SH_RES	Ratio of renewable to total electricity production	Ratio
POP	Population on 1 January	People
GINI	Gini coefficient of equivalised disposable income	Index
IMPORTER	Takes value=1 if energy dependency > 0	Dummy
EU-15	Takes value=1 if country belonged to the EU-15	Dummy
CRISIS	Takes value=1 for the period 2008-2012	Dummy
t	Time trend	Index

[17] We follow the Eurostat definition of energy dependency by applying this expression:

Energy Dependency = (Imports – Exports) / Gross Available Energy

Thus, a negative dependency rate indicates a net exporter of energy while a dependency rate in excess of 100% indicates that energy products have been stocked.

Table 2. Descriptive statistics

Variable	*Mean*	*Std. Dev.*	*Min.*	*Max.*
GDP	503,035	740,183	7,166	2,904,845
CO2	91.81	9.10	57.60	124.90
E_EQ	88.74	11.92	30.50	99.70
L	7,592	9,850	148	40,636
K	4,190,000	6,030,000	46,200	21,200,000
E	61,311	82,288	719	357,048
SH_RES	18.55	14.51	0.12	72.75
POP	17,700,000	22,700,000	402,668	82,800,000
GINI	29.71	3.98	20.90	40.20
IMPORTER	0.94	0.23	0	1
EU-15	0.53	0.50	0	1
CRISIS	0.36	0.48	0	1
t	7.60	4.00	1	14

5. Results

5.1 Parameter Estimates and Environmental Technical Efficiency

We use the enhanced hyperbolic distance function with a translog specification described in Equation (5) and the inefficiency term presented in Equation (6). To control for unobserved heterogeneity, we employ a fixed effects model that includes country-specific dummies.[18] The parameters estimated are presented in Tables 3 and 4.[19] The variables have been divided by their geometric mean, which means that the estimated function is a Taylor series approximation of the real, though unknown, distance function at the mean of the data. Therefore, the coefficients can be directly interpreted as elasticities at the sample mean.

Table 3 shows that the estimated enhanced hyperbolic distance function, at the sample mean, satisfies the regularity conditions, i.e., it is nondecreasing in desirable outputs and nonincreasing in the undesirable output and inputs.[20] Through our control variables we observe that a higher share of renewable energy sources in electricity production and being a net energy importer have a positive impact on technology. On the contrary, a larger population and the strike of the economic crisis imply a greater need for resources.

[18] This means estimating the model using "a brute force maximum likelihood" approach (Filippini et al., 2008, p.175) as an alternative to the True Fixed Effects (TFE) model proposed by Greene (2005a; 2005b).
[19] These estimates are obtained using a standard maximum likelihood procedure.
[20] However, it should be highlighted that this by no means implies that the monotonicity condition is automatically satisfied for the whole domain of our function. Barnett et al. (1996) show that violations of this requirement are frequent for most functional forms.

Table 3. Parameter estimates of the enhanced hyperbolic distance function – Frontier (Eq. 5)

Parameters	***Coef.***	***z***	***P > |z|***
$\ln GDP_{it}$	–0.200	–24.49	0.001
$\ln CO2_{it}$	0.046	4.39	0.001
$\ln E\_EQ_{it}$	–0.157	–10.29	0.001
$\ln L_{it}$	0.217	17.28	0.001
$\ln K_{it}$	0.325	24.99	0.001
$\ln E_{it}$	0.055	4.97	0.001
t	0.001	0.92	0.355
$\frac{1}{2} (\ln GDP_{it})^2$	–0.064	–3.32	0.001
$\frac{1}{2} (\ln CO2_{it})^2$	0.088	1.08	0.281
$\frac{1}{2} (\ln L_{it})^2$	–0.011	–0.36	0.717
$\frac{1}{2} (\ln K_{it})^2$	–0.025	–0.96	0.337
$\frac{1}{2} (\ln E_{it})^2$	–0.107	–2.76	0.006
$\frac{1}{2} t^2$	–0.001	–2.20	0.027
$\ln GDP_{it} \cdot \ln CO2_{it}$	0.009	0.31	0.757
$\ln L_{it} \cdot \ln K_{it}$	0.054	1.91	0.056
$\ln L_{it} \cdot \ln E_{it}$	0.051	1.75	0.079
$\ln K_{it} \cdot \ln E_{it}$	–0.053	–2.31	0.021
$\ln L_{it} \cdot \ln GDP_{it}$	–0.080	–3.98	0.001
$\ln K_{it} \cdot \ln GDP_{it}$	0.044	2.35	0.019
$\ln E_{it} \cdot \ln GDP_{it}$	0.102	4.58	0.001
$\ln L_{it} \cdot \ln CO2_{it}$	0.046	1.24	0.215
$\ln K_{it} \cdot \ln CO2_{it}$	0.055	1.75	0.080
$\ln E_{it} \cdot \ln CO2_{it}$	–0.139	–3.62	0.001
$\ln GDP_{it} \cdot t$	–0.003	–3.88	0.001
$\ln CO2_{it} \cdot t$	–0.005	–3.19	0.001
$\ln L_{it} \cdot t$	0.001	0.97	0.334
$\ln K_{it} \cdot t$	0.004	6.61	0.001
$\ln E_{it} \cdot t$	–0.003	–2.90	0.004
$\frac{1}{2} (\ln E\_EQ_{it})^2$	–0.239	–5.06	0.001
$\ln E\_EQ_{it} \cdot \ln CO2_{it}$	0.040	0.74	0.461
$\ln L_{it} \cdot \ln E\_EQ_{it}$	0.221	6.58	0.001
$\ln K_{it} \cdot \ln E\_EQ_{it}$	–0.013	–0.67	0.503
$\ln E_{it} \cdot \ln E\_EQ_{it}$	–0.349	–9.20	0.001
$\ln E\_EQ_{it} \cdot t$	–0.001	–0.06	0.953
$\ln POP_{it}$	–0.192	–6.86	0.001
SH_RES_{it}	0.001	1.86	0.063
$IMPORTER_{it}$	0.028	6.06	0.001
$GINI_{it}$	0.001	0.16	0.873
$CRISIS_t$	–0.002	–1.91	0.057
Intercept	2.903	6.54	0.001
Log-likelihood		1383.665	

As far as the EE is concerned, Table 4 displays the effect of the determinants of the technical environmental efficiency.

Table 4. Parameter estimates of the enhanced hyperbolic distance function – Inefficiency term (Eq. 6)

Parameters	***Coef.***	***z***	***P > |z|***
Noise term [ln (σ^2_v)]			
Intercept	–10.030	–122.91	0.001
Inefficiency term [ln (σ^2_u)]			
SH_RES_{it}	–0.839	–6.10	0.001
$EU\text{-}15_i$	–3.301	–4.54	0.001
$GINI_{it}$	–4.686	–1.18	0.237
t	–0.001	–0.01	0.991
Intercept	12.468	0.93	0.351

Negative coefficients of the variables displayed in Table 4 indicate that inefficiency decreases as these variables increase and vice versa. Thus, the results indicate that having a higher relative share of renewable energy sources decrease environmental technical inefficiency. Thus, this result shows that renewable energy sources are a significant factor to increase efficiency. In addition, countries belonging to the EU-15 group present lower inefficiency indices.

From these estimates and taking advantage of Equations (12) and (13), we can compute the *Subs* indicators and hence obtain information about the degree of substitutability/complementarity between outputs. The value of the indicator for the two desirable outputs (GDP and energy equity) is 1.28, while for GDP and CO_2, and energy equity and CO_2, they are –4.35 and –0.29 respectively. It should be recalled that the higher the *Subs* indicator is (in absolute value), the greater the opportunity cost of substituting one for another (i.e., the greater the complementarity). Therefore, our results show that CO_2 emissions abatement is more complementary to GDP than to energy equity. However, we also find that GDP and energy equity are quite complementary. In summary, these results seem to highlight the pivotal role of a sustainable economic development with clean energies for both slashing CO_2 emissions and fostering energy equity.

From the estimation of the model, it is also possible to construct EE indices according to Equation (7). It is worth nothing that the environmental technical efficiency estimates are higher in the enhanced hyperbolic distance functions than in other distance function specifications (e.g., hyperbolic or output-oriented) because they represent "a more comprehensive path toward the production frontier in so far as firms can adjust both sets of outputs –desirable and undesirable– as well as inputs" (Cuesta et al., 2009, p.2240). As a result, in our model, the estimated environmental efficiency values are very close to the frontier. For example, Norway and Sweden have EE values extremely close to 100% indicating that these countries are the ones that are utilising resources in a more optimal way compared to the other countries in the sample. On the other hand, Malta is the country that exhibits the lowest level of efficiency (EE = 0.94). In Figure 1, the countries are presented sorted in increasing order according to their average EE index.

Figure 1. Average EE by country (period 2005-2018)

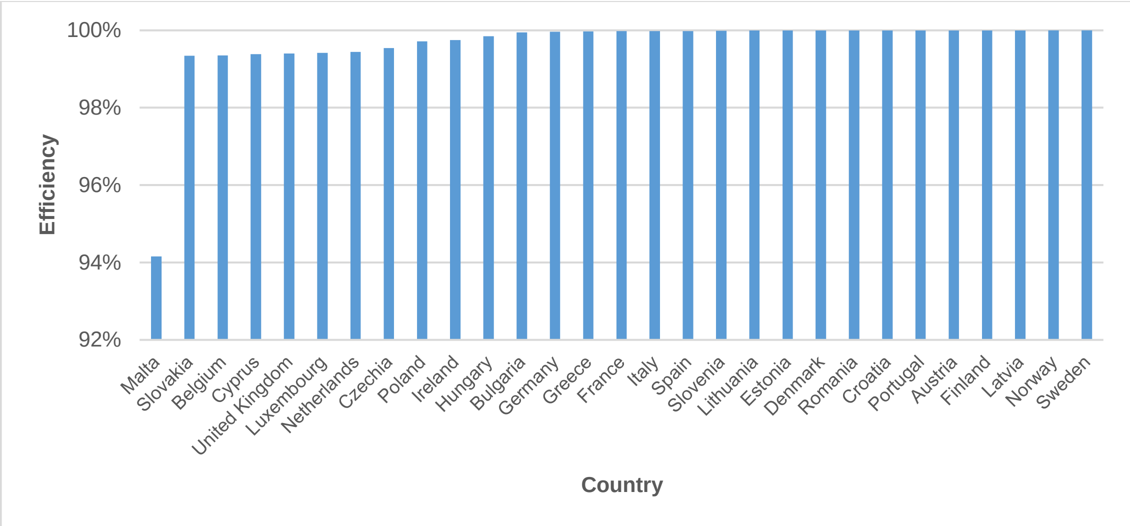
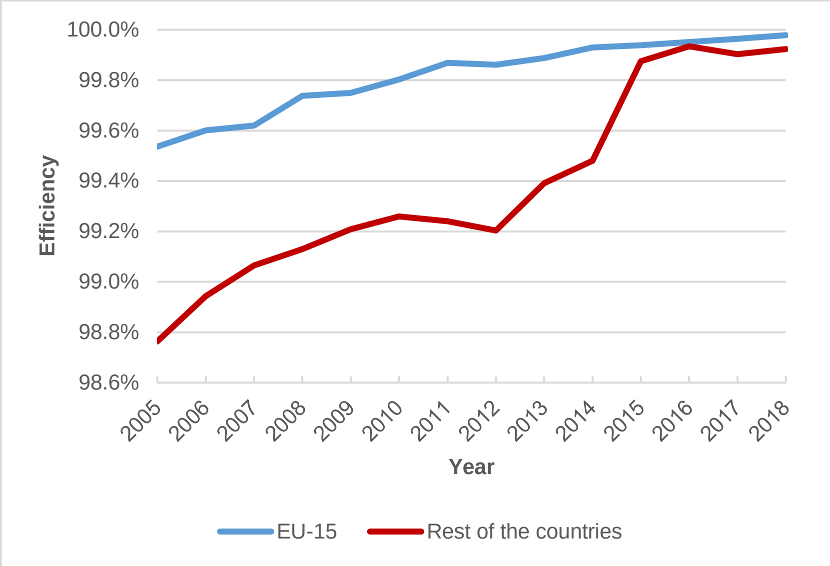


Figure 2 shows the evolution of the average EE indices over time. A positive trend towards the maximum level of efficiency can be observed, i.e., the countries in our sample have improved their performance over time. However, the pattern seems to be different for the EU-15 countries than for the rest of the countries. In the next section we will go one step further in the analysis to identify whether there has been convergence or divergence between those countries.

Figure 2. Evolution of the EE



5.2. Analysis of Beta and Sigma Convergence

Figure 3 shows the change in the coefficient of variation of the EE indices for both sets of countries during the period 2005-2018. The graph seems to confirm the existence of sigma convergence. However, the pattern is different depending on the group of countries. Whilst in general terms there is a steady downward trend in the coefficient of variation for all European countries, the evolution is different. We can see that, initially, the coefficient of variation is higher (and even augments until 2012 before sharply declining) for countries that do not belong to the EU-15 group. The drop of this coefficient in absolute terms during the analysed period is 2.6 times bigger in the case of the non-EU-15 compared to the EU-15 countries. Nevertheless, in percentage terms, the decrease of the coefficient of variation for the EU-15 group (95%) is slightly greater than for the other group of countries (93%).

Before carrying out the econometric analysis of the beta convergence, Figures 4a and 4b reveal a first approximation to this concept for the different European countries in the period studied. The annual growth rate of the EE index is presented on the vertical axis and the EE value for the initial period (in logarithms) on the vertical axis.

Figure 3. Sigma convergence

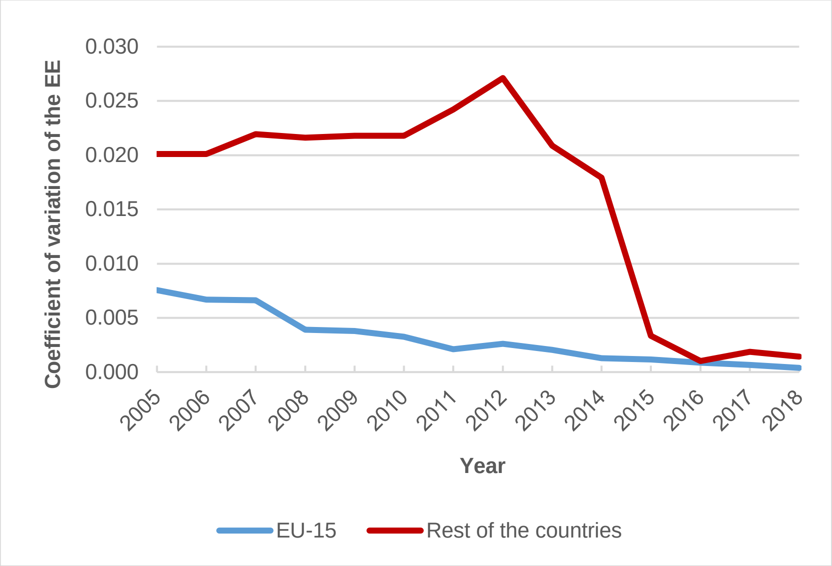


Figure 4a. Beta convergence (EU-15)

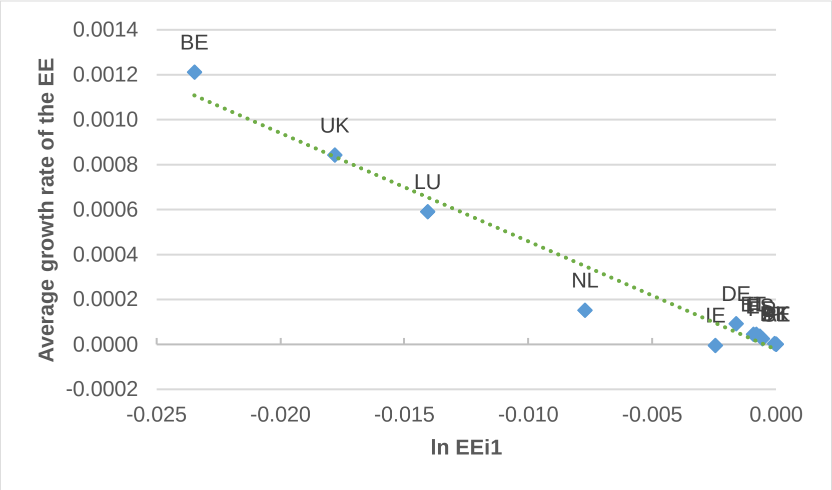
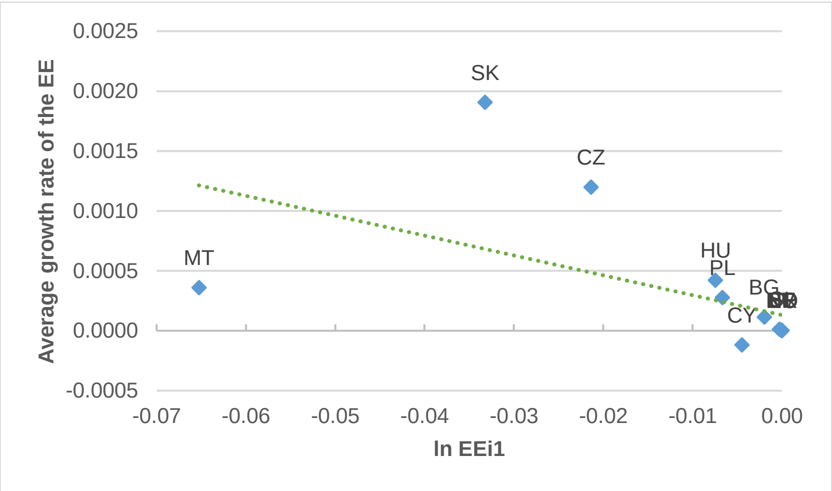


Figure 4b. Beta convergence (rest of the countries)



These graphs show a negative correlation between the initial efficiency indices and their average growth rate. This inverse relationship between both magnitudes indicates that the economies that present a higher growth rate tend to be those that started with lower levels of efficiency in the initial period, which can be said that justifies the convergence analysis. For example, with respect to the EU-15 countries (Figure 4a), Belgium and UK, which are the countries that started in the least favourable situation, are also the ones with the highest average growth rate in the analysed period. Similarly, for the rest of the countries (Figure 4b), Slovakia, which started with the second lowest level of efficiency in the first year of the sample, is the country that shows the highest average growth rate.

Considering these observations, an econometric model is then proposed to statistically test the existence of conditional and absolute beta convergence based on the estimation of Equation (14). Absolute and conditional beta convergence imply that the coefficient of the variable to be analysed for convergence (coefficient *b*) is significantly lower than zero.

In first place, the results of the estimation of Equation (14) refer to absolute beta convergence. The results presented in Tables 5a and 5b confirm the existence of absolute beta convergence between countries for both groups, EU-15 and the rest of the countries (the estimated coefficient for the initial efficiency level of the countries is significant and less than zero). Moreover, using Equation (15) the speed of convergence can be calculated. Results indicate that the speed of convergence is higher for the case of the EU-15 countries (0.0035) compared to the rest (0.0012).

Table 5a. Absolute beta convergence estimates (EU-15)

Parameters	***Coef.***	***z***	***P > |z|***
Intercept	–0.001	–1.02	0.327
ln EE_{i1}	–0.048	–18.62	0.001
Speed of Convergence	0.0035		
R-squared	0.96		

Table 5b. Absolute beta convergence estimates (rest of the countries)

Parameters	***Coef.***	***z***	***P > |z|***
Intercept	0.001	0.86	0.407
ln EE_{i1}	–0.016	–2.24	0.045
Speed of Convergence	0.0012		
R-squared	0.29		

Regarding conditional beta convergence, we include the average ratio of renewable to total electricity production in each country, given that it has proven to be significant in explaining the efficiency indices. The estimates, presented in Tables 6a and 6b, also show a negative and significant *b* coefficient, which confirms the conditional beta convergence. The share of renewables is significant for the EU-15 countries, indicating that for this group of countries, a higher share of renewables in electricity production might help countries that are lagging behind to achieve their optimal level of EE.

As far as the speed of convergence is concerned, and using Equation (15) again, it is higher for the case of the EU-15 countries (0.0040) compared to the rest of the European countries of our sample (0.0022).

Table 6a. Conditional beta convergence estimates (EU-15)

Parameters	***Coef.***	***z***	***P* > |*z*|**
Intercept	–0.001	–3.36	0.006
ln EE_{i1}	–0.055	–18.70	0.001
SH_RES_i	0.001	3.14	0.008
Speed of Convergence		0.0040	
R-squared		0.98	

Table 6b. Conditional beta convergence estimates (rest of the countries)

Parameters	***Coef.***	***z***	***P* > |*z*|**
Intercept	–0.001	–0.950	0.364
ln EE_{i1}	–0.029	–2.180	0.052
SH_RES_i	0.001	1.120	0.287
Speed of Convergence		0.0022	
R-squared		0.37	

6. Discussion and Conclusions

The EU has committed to attain carbon neutrality by 2050 and thereby become the first continent to achieve that milestone. Several policy plans have recently been proposed and signed to foster the attainment of that decarbonisation goal. However, achievement of the objective goes hand in hand with the challenges of ensuring the competitiveness and economic development of the European countries, without forgetting justice and inclusiveness.

Those challenges are explicitly connected with the so-called energy trilemma that concerns with the interplay of energy security, energy affordability, and environmental sustainability. Moreover, due to the global nature of the overarching problem to be tackled, i.e., climate change, it is paramount that all countries be on board, and no one lags behind in order to guarantee that the decarbonisation objective is reached. Therefore, to better understand the green energy transition process and its practical feasibility, two important questions need to be answered. First, is it possible to simultaneously manage the economic, environmental, and equity challenges? And second, are the countries on track to addressing those challenges? If the answer to either of these questions is 'no,' some policy aspects will need to be reconsidered to address the issue of climate change mitigation.

To help respond to these two questions, we propose the application of an enhanced hyperbolic distance function in the context of a stochastic frontier analysis framework. Through that approach, we are able to model the joint attainment of economic development, environmental sustainability, and energy equity, and assess the efficiency with which European countries are carrying out the green energy transition. Our model is applied to an unbalanced panel of 29 European countries for the period 2005-2018. We distinguish between EU-15 and non-EU-15 countries in our sample to analyse beta and sigma convergence in environmental efficiency.

We define our distance function using three outputs, two of them desirable (GDP and the percentage of non-energy-poor people) and one undesirable (CO_2 emissions). At the same time, we assume that countries use three inputs as factors of production in the economy: labour, capital, and energy. In addition, we also consider the ratio of utilisation of non-renewable to renewable energy sources in electricity generation, population, a Gini coefficient, the condition of net importers/exporters of energy of the countries, and a dummy to capture the impact of the 2007-2008 economic crisis as control variables.

Our estimates show that the average environmental technical efficiency of the European economies has improved throughout the studied period. However, the patterns of progress have been different, showing the non-EU-15 countries a steeper evolution than the EU-15 ones. Moreover, our results also show that CO_2 emissions abatement is more complementary to GDP than to energy equity. However, we also observe that GDP and energy equity are quite complementary. In summary, these results seem to highlight the pivotal role of a sustainable economic development with clean energies for both slashing CO_2 emissions and fostering energy equity. This seems to support the idea that it is possible to concurrently handle the economic, environmental, and equity goals along the green transition. Finally, we find sigma convergence for both groups of countries, being slightly higher for the EU-15 countries. Additionally, we also find absolute and conditional beta convergence for the both the EU-15 and the non-EU-15 countries. To conclude, we show that a higher percentage of renewables helps countries that are lagging behind to achieve their optimal level of EE.

In general, the results obtained in this paper are encouraging and serve to envisage an economically prosperous green transition that is fair and inclusive. Moreover, despite the differences between countries in dealing with our defined energy trilemma, the convergence analyses seem to confirm that the gap between countries is decaying over time and the set of countries in our sample seems to be rowing in the same direction. Nevertheless, we should not forget that despite the compatibility of objectives and the constant improvement in the environmental technical efficiency, these outcomes may not ensure that the 2050 climate neutrality ambition is achieved.

There are several factors that will be vital to manage the trade-offs between the energy trilemma dimensions while the decarbonisation goals are reached. First, focus needs to be kept on innovation and deployment of key technologies (e.g., Carbon Capture, Utilisation and Storage – CCUS) and the promotion of renewable energy sources. This is essential to decouple economic activity from resource use (e.g., free and infinitely available wind and sun vs. non-free and depletable fossil fuels), while at the same time decoupling economic activity from environmental impact. Second, energy efficiency and demand flexibility ought to become prominent to both reduce and shift energy use throughout the day. These strategies have impacts on the utilisation of the energy grids and can be seen as more cost-effective solutions than investments in new infrastructure, which in turn may help reduce energy costs and boost energy affordability. Third, energy security needs to be enhanced by reducing the EU’s dependence on energy imports and diversifying sources while maintaining energy supply at affordable prices, something that does not look straightforward in the current geopolitical context. Finally, there is a need to consider aspects beyond the energy sector and the climate goals when thinking about environmental sustainability. The tendency should be to look at a broader and more integrated level of energy systems. One good example is represented by the water-energy nexus that defines the interactions between the water used for energy production and the energy used for water and wastewater treatment. The current situation raises serious environmental issues of water stress that should be carefully considered in addition to climate change.

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