Environmental Efficiency of European Industries across Sectors and Countries

Stergiou, Eirini

Department of Economics, University of Patras, Greece

20 September 2022

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Eirini Stergiou[a]

e.stergiou@upnet.gr

Abstract

Green growth is recognized as the fundamental development strategy in Europe due to the immense pressure of environmental pollution, economic growth and energy usage. In this study, a non-radial directional distance function is used to measure environmental efficiency (ENE) of 54 industries from 28 European countries across the three sectors of an economy over the 2000-2014 period. The complexity of heterogeneity is examined by incorporating the metafrontier approach under distinct group frontiers. The results reveal that industries present higher levels of environmental efficiency within their sectors while manufacturing industries achieved the lowest progress in environmental efficiency. Thus, it is critical to introduce and implement sector-oriented policies rather than common guidelines for all European countries.

keywords: Environmental efficiency, Directional distance function, Metafrontier, Heterogeneity, European industries

JEL Classifications: C44, D29, L23, Q01, Q56

*Corresponding Author,e.stergiou@upnet.gr

[a]Department of Economics, University of Patras, Rio 26504, Patras, Greece.

1 Introduction and Motivation

Environmental issues have become one of the most important problems worldwide due to the rapid economic development and the intensive levels of industrialization. As sustainability includes economic, social and environmental issues, among others, the incorporation of sustainable methods in the production process benefits the long-term growth and the well-being of humans (European Environment Agency, 2022). In this sense, various regulatory and environmental policies have been established so that societies minimize energy consumption and reduce greenhouse gas (GHG) emissions. The United Nations Framework Convention on Climate Change (UNFCCC) has made several efforts to stabilize GHG emissions at certain levels assigning different responsibilities for Annex I and Annex II countries. However, its success has been widely criticized as some parties do not adhere to the commitments due to the costs of mitigating emissions.

In this regard, the evaluation of environmental efficiency has become a key point towards sustainability as it provides substantial practical guidelines to policymakers. Scholars and governments are being involved with its estimation because of its ability to reflect the relation between economic growth and undesirable outcomes, namely environmental problems such as air pollution. More specifically, it provides policymakers, or any other interested parties, practical knowledge that will make their decisions more consistent, objective and successful. In literature, a variety of parametric and nonparametric techniques, the Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA) method respectively, have been applied to measure environmental efficiency. In general, the benchmarking technique of DEA has been widely used to evaluate environmental performance (i.e. Färe et al., 2004; Zhou et al., 2008; Halkos and Tzeremes, 2014; Kounetas, 2015; Zhang et al., 2015; Allevi et al., 2019). Nevertheless, the Directional Distance Function (DDF) has displaced the DEA method as the latter treats undesirable outputs as inputs. Conversely, the DDF approach, proposed by Chambers et al. (1996), has the ability of modeling the joint production of inputs, desirable (such as GDP) and undesirable outputs (such as CO_2) simultaneously and it can also be regarded as a generalized form of Shephard's distance function (Shephard, 1970).[1] The limitation of traditional DDF is that it reduces inputs/bad outputs and expands good outputs at the same rate, overestimating efficiency levels that results to an incorrect ranking of the Decision Making Units (DMUs). To overcome this prob-

[1]The major advantage of both DEA and DDF approach is that they do not require the imposition of any specific functional form of the environmental technology.

lem, Zhou et al. (2012) presented a non-radial measure that incorporates slacks into DDF. The non-radial DDF method has been used in a plethora of energy and environmental studies as it allows the disproportionate expansion/reduction of the variables (see e.g. Wang et al., 2013, 2016; Lee and Choi, 2018; Zhou et al., 2019; Stergiou and Kounetas, 2021b).

However, the aforementioned studies treat DMUs as an homogenous group that uses the same environmental technology. Many researchers have underlined the importance of heterogeneity among DMUs (Yao et al., 2015; Long et al., 2018; Zhu et al., 2018; Stergiou and Kounetas, 2022). When heterogeneity exists, it causes unbiased evaluation of energy, eco and environmental efficiency.[2] Technology innovation, resource availability, environmental regulations, national and sectoral conditions may provoke differences in environmental costs among DMUs and influence the efficiency levels asymmetrically (Kumar and Khanna, 2009; Lin et al., 2013; Stergiou and Kounetas, 2021b). The seminal works of Battese et al. (2004) and O'Donnell et al. (2008) who proposed the metafrontier approach, allow the estimation of efficiency and the corresponding technology gaps when DMUs are divided into different groups based on their specific characteristics. Thus, the incorporation of the metafrontier concept in the analysis reveals possible differences between intra-group and inter-group efficiency levels.

In this paper a unique panel dataset of 54 industries that belong to different sectors and 28 European countries is employed to estimate their environmental efficiency for the period 2000-2014. More specifically, this research aims at enlightening the role of technology heterogeneity among industries that may be caused due to distinct sectoral and national characteristics. To the best of my knowledge, this is the first work that examines to such an extent industrial environmental performance across the three sectors and different European countries by incorporating the metafrontier framework in a versatile way. By utilizing the non-radial DDF method and the concept of the metafrontier, the methodological development of an hierarchical environmental technology becomes apparent and the evaluation of industrial environmental efficiency is feasible under three levels of technology frontiers. To be exact, industries from different sectors and European countries are being evaluated and benchmarked with respect to the sectoral, national and European frontier. In this way, any heterogeneity that exists across the sectors and countries is taken into account and the environmental effi-

[2]Environmental efficiency differs from eco-efficiency in the sense that the former also includes inputs variables in its estimation while the latter takes into account only the good and bad outputs in the production technology set.

ciency of each industry is computed based on the (i) sector that belongs (primary, secondary and tertiary) (ii) European country (iii) European Union.

The results of this study can shed some light on how concerns about the environmental performance of industries could be translated into efficacious information for policymakers towards sustainability. The calculation of the technology gaps operating under various cluster technologies revealed that the effectiveness of the regulations may not be optimal for the entire set of industries. Because of the different patterns of environmental efficiency, considerable attention should be given to the specific characteristics of each sector and EU country with reference to their economic growth, industrial competitiveness and structure and the different levels of resource endowment.

The remainder of this paper is organized as follows. Section 2 presents the methodological framework of the non-radial DDF model and the different levels of the metafrontier approach. Section 3 describes the data employed in the empirical study. The empirical results are presented and discussed in Section 4 while Section 5 concludes.

2 Methodology

2.1 The Concept of Different Technology Frontiers

As already mentioned in the introduction section, many studies incorporate in their analysis the concept of metafrontier in order to examine the role of heterogeneity of production technology in the efficiency scores. More specifically, this study investigates the notion of metafrontier under three aspects: the comparison and benchmarking of DMUs with others (i) within sectoral groups (frontier case), (ii) within national groups (metafrontier case) and (iii) within a common European group (meta-metafrontier case). The aforementioned cases are displayed in Figure 1.

The hypothesis of a metaproduction function is that all DMUs, namely industries, from different groups (sectors, countries) could potentially have access to the same technology. Thus, it is considered as an envelope of the distinct groups' frontiers in which all observations of the groups define the metafrontier set (O'Donnell et al., 2008). When a unified production technology is considered, the physical, social, institutional and economic environment (Kounetas, 2015; Stergiou and Kounetas, 2021a, 2022) and national, legal and institutional regulations (Halkos and Tzeremes, 2011) are being eliminated. However, due to heterogeneity and their capability to assimilate the existing knowledge and technology, industries can be compared with others from another sector or country. As depicted in Figure 1, the meta-metafrontier (MMF) is enveloped by the national frontiers (I,II,...,K) with different production technologies and the metafrontier (MF) by the sectoral technology frontiers. Consider an industry under evaluation, denoted by point A, that uses an input vector to produce both desirable and undesirable output. The specific industry has access to the technological set of the sectoral frontier and simultaneously to the technology of national metafrontier (common to all industries) and European meta-metafrontier. The industry can move towards point B, C and D in order to become fully environmental efficient with reference to the corresponding technology frontier.

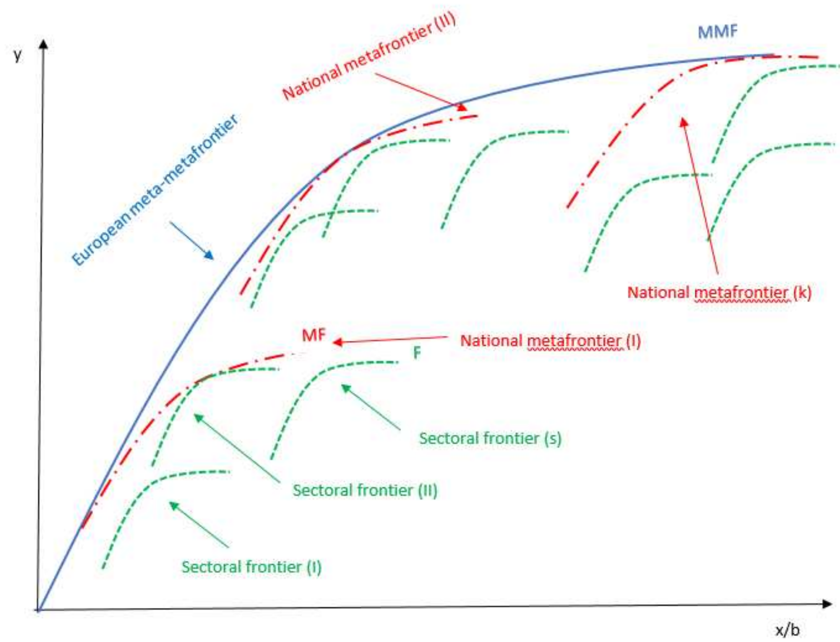

Figure 1: The different concepts of technology frontier

2.2 Non-Radial DDF and Environmental Efficiency

Assume there are n industries (n=1,...,N) of s sectors (s=1,..,S) of the economy from k European countries (k=1,...,K). Each industry uses m inputs x $\in R_+^M$ to produce l desirable $y \in R_+^L$ and j undesirable outputs $b \in R_+^J$. The production technology set (P) can be described as follows:

$$P = \{(x, y, b) : x \text{ can produce } (y,\ b)\} \tag{1}$$

where P is assumed to satisfy the standard axioms of production theory and the strong disposability of input and desirable output. P can also be referred to as an environmental production technology set if the weak disposability and the null-jointness assumption are imposed. For each n industry -DMU- the technology can be defined as:

$$
\begin{aligned}
P = \{(x, y, b) : & \sum_{n=1}^{N} \lambda_n x_{mn} \leqslant x_{m0}, m = 1, ..., M \\
& \sum_{n=1}^{N} \lambda_n y_{ln} \geqslant y_{l0}, l = 1, ..., L \\
& \sum_{n=1}^{N} \lambda_n b_{jn} = b_{j0}, j = 1, ..., J \\
& \lambda_n \geq 0, n = 1, ..., N\}
\end{aligned} \tag{2}
$$

where λ_n is the intensity variables that serves as the convex combinations of inputs and outputs in the formation of environmental production technology. To overcome the efficiency's overestimation when employing the traditional DDF method, Zhou et al. (2012) defined a non-radial DDF approach that can be expressed as follows:

$$
\overrightarrow{D_P}(\mathbf{x{,}y{,}b;g}) = sup\big\{\mathbf{w}^P\beta : ((\mathbf{x{,}y{,}b}) + diag(\beta) * \mathbf{g})\epsilon \text{ P}\big\} \tag{3}
$$

where $\mathrm{w}^P = (\mathrm{w}^x, \mathrm{w}^b)^P$ describes a normalized weight vector relevant to the number of inputs and outputs, $g = (-x, 0, -b)$ is the directional vector employed in the study and $\beta = (\beta_x, \beta_b)^P \geq 0$ represents the vector of the scaling factors.[3] However, the directional vector g can be set up in different ways according to the policy goals of each economy. The value of $\overrightarrow{D_P}$ can be estimated by solving the following linear programming problem:

$$
\begin{aligned}
& \overrightarrow{D}_P(x^q, y^q, b^q; g) = \max \ \mathrm{w}^x_m\beta^x_m + \mathrm{w}^b_j\beta^b_j \\
s.t. \quad & \sum_{n=1}^{N} \lambda_n x_{nm} \leq x'_m - \beta^x_m g_{xm}, \quad m = 1, ..., M \\
& \quad \sum_{n=1}^{N} \lambda_n y_{nl} \geq y'_l, \quad l = 1, ..., L \\
& \sum_{n=1}^{N} \lambda_n b_{nj} = b'_j - \beta^b_j g_{bj}, \quad j = 1, ..., J
\end{aligned} \tag{4}
$$

[3]If $\overrightarrow{D}$ is equal to zero, the industry will be efficient and will be located along the best-practice frontier in the g direction. In this study, the direction gives the advantage of examining environmental efficiency by considering how much an industry can diminish its inputs and undesirable output while keeping the same level of desirable output.

$$\lambda_n \geq 0, \quad \beta^x_m, \beta^b_j \geq 0$$

In Equation (4), β^x and β^b denote a simultaneous decrease of inputs and undesirable outputs respectively at a given level of desirable output. Thus, the model seeks to reduce the inputs, namely capital, labor, energy use and intermediate inputs and additionally CO_2 emissions non-proportionally in order to find a benchmark in the performance evaluation. Supposing that β^{*x} and β^{*b} describe the optimal solutions of (4) and given the fact that the DDF approach estimates the inefficiency scores of the DMUs, Environmental Efficiency (ENE) can be formulated as:

$$ENE = 1 - \frac{1}{M+J}(\sum_{m=1}^{M} \beta^{*x}_m + \sum_{j=1}^{J} \beta^{*b}_j) \tag{5}$$

The measure of ENE lies between zero and unity. A larger ENE implies better environmental performance. If ENE is equal to unity, the industry presents the best performance and is fully environmental efficient.

In the frontier case, each industry operates under exactly one production technology, namely the sector group. For instance, an industry from the manufacturing sector can only be compared and benchmarked with industries from the same sector within the same country. However, when the MF and MMF are considered, each industry can be compared with others operating under different technologies. As demonstrated in Figure 1, the MF technology includes all industries from all three sectors of an economy (Battese et al., 2004). Conversely, the MMF technology is defined as a 'wider', unified, common frontier that comprises all industries from all sectors and countries of Europe. Therefore, the metatechnology and meta-metatechnology set, denoted as P^{MF} and the P^{MMF} respectively, can be described as:

$$P^{MF} = conv\{P^1, P^2, ..., P^S\} \quad \text{or} \tag{6}$$

$$\begin{aligned} P^{MF} = \{&(x, y, b) : x \; can \; produce \; (y, \; b) \\ &in \; at \; least \; one \; of \; P^1, P^2, ..., P^S\} \end{aligned} \tag{7}$$

$$\text{and} \quad P^{MMF} = conv\{P^{MF1}, P^{MF2}, ..., P^K\} \quad \text{or} \tag{8}$$

$$\begin{aligned} P^{MMF} = \{&(x, y, b) : x \; can \; produce \; (y, \; b) \\ &in \; at \; least \; one \; of \; P^{MF1}, P^{MF2}, ..., P^K\} \end{aligned} \tag{9}$$

The environmental efficiency scores under the MF (ENE_{MF}) and MMF (ENE_{MMF}) technology can be easily obtained by solving the analogous linear programming problems as in 4.

2.3 Technology Gap Ratio of Environmental Efficiency

Following O'Donnell et al. (2008), the technology gap ratio of environmental efficiency between the group frontier, metafrontier and meta-metafrontier can be estimated as:

$$TGR_1^n = \frac{ENE_{MF}^n}{ENE_F^n} \tag{10}$$

and

$$TGR_2^n = \frac{ENE_{MMF}^n}{ENE_{MF}^n} \tag{11}$$

Equations 10 and 11 refer to the technology gap ratios of the nth industry with reference to the corresponding frontier. TGR_1 is calculated by taking into account the group frontier (sectors) and the metafrontier (countries) while TGR_2 the countries and the meta-metafrontier (Europe). Since ENE_F, ENE_{MF} and ENE_{MMF} are measured based on group frontier, metafrontier and meta-metafrontier respectively, the relationship $\text{ENE}_F \leq \text{ENE}_{MF} \leq \text{ENE}_{MMF}$ is apparent. Both TGRs also lie between zero and unity. When TGR is closer to unity, the heterogeneity of production technology is smaller and the frontiers are closer together. Conversely, when TGR is closer to zero, the heterogeneity is greater and the distance between the frontiers increases.

3 Data and Variables

In order to examine the environmental efficiency, we use data for 54 industries from the primary (agriculture and mining), secondary (manufacturing) and tertiary (service) sector of an economy, as shown in Table A1. The primary sector includes industries from A01 to A03, the secondary from B to F and the tertiary from G45 to R_S. The study includes industrial data from 28 countries across Europe[4] over the 2000-2014 period.[5] Four factors were selected as inputs and two as outputs. Capital stock (K), Labor (L), Intermediate Inputs (II) and Energy use

[4] Austria (AUT), Belgium (BEL), Bulgaria (BGR), Cyprus (CYP), Czech Republic (CZE), Germany (DEU), Denmnark (DNK), Spain (ESP), Estonia (EST), Finland (FIN), France (FRA), Great Britain (GBR), Greece (GRC), Croatia (HRV), Hungary (HUN), Ireland (IRL), Italy (ITA), Lithuania (LTU), Luxembourg (LUX), Latvia (LVA), Malta (MLT), Neterlands (NLD), Poland (POL), Portugal (PRT), Roumania (ROU), Slovakia (SVK), Slovenia (SVN), Sweden (SWE).

[5] Industries, countries and time period were exclusively chosen on the basis of the availability of key variables.

(E) are employed as inputs whilst Gross Value Added (GVA) and Carbon dioxide emissions (CO_2) as the desirable and undesirable output respectively. Capital is expressed in million Euros, labor is captured by the total hours worked by employees, expenditure on intermediate inputs in million Euros and energy in Terajoules. For the output set, GVA is measured in million Euros and CO_2 emissions in kilotons.[6] Data were drawn from the World Input Output Database (WIOD). Table 1 and Figure 2 present the descriptive statistics and the growth rates of the selected variables respectively. GVA along with the total number of inputs exhibit analogous growth rates, albeit with different peaks and valleys. Energy and carbon emissions display a similar average growth pattern throughout the sample period with a significant sharp decline in 2009. At the end of the sample period, both variables present a negative growth rate indicating an encouraging sign towards the achievement of carbon neutrality targets.

Table 1: Variables and descriptive statistics

	Variable	Observations	Mean	Standard Deviation	Min	Max
Inputs	K	18630	127234.700	1055627	0.922	3.55e+07
	L	18630	17005.950	67915.910	1.01	1531510
	E	18630	70809.380	372587.900	0.015	6466591
	II	18630	37921.020	171968	4.100	5555210
Outputs	GVA	18630	30129.130	115489.500	3.400	2269014
	CO_2	18630	2553.569	13784.600	0.002	359012.200

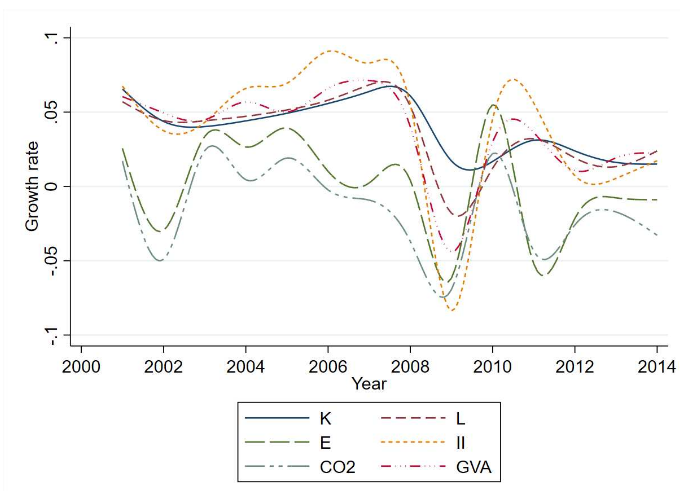

Figure 2: Growth rate of the variables throughout the sample period

[6]The monetary variables have been deflated to 1995 prices.

4 Results and Discussion

4.1 Environmental Efficiency

In order to estimate environmental efficiency of industries across the different sectors and European countries we employ the non-radial DDF approach as discussed in Section 2.2. However, due to technology transfer, knowledge diffusion and other economic and social factors, industries tend to converge as their adaptation effectiveness becomes vigorous. Thus, the concept of metafrontier and meta-metafrontier are fundamental for the appropriate evaluation of environmental efficiency in sectoral, national and European level.[7] More specifically, under the frontier, industries of each sector use different technologies and operate under distinct sectoral frontiers. Under the metafrontier, even though industries from different sectors can be compared with each other, the benchmarking arises inside the boundaries of their country. Lastly, in the case of the MMF, industries use the same technology and face an identical European frontier in order to examine the inter-group levels of environmental efficiency.

Table 2: Environmental efficiency in different time periods

Period	ENE_F	ENE_{MF}	ENE_{MMF}
2000-2004	0.835	0.687	0.262
	(0.238)	(0.291)	(0.166)
2005-2009	0.819	0.680	0.266
	(0.248)	(0.292)	(0.174)
2010-2014	0.818	0.685	0.275
	(0.251)	(0.294)	(0.188)
2000-2014	0.824	0.684	0.268
	(0.246)	(0.292)	(0.177)

Note: Standard deviation in parentheses

At first glance, Table 2 presents the scores under the three production technologies in specific time periods. Overall, the results point out that environmental efficiency is overestimated when technological heterogeneity is not incorporated in the analysis. Moreover, the comparison between time periods indicates an increase for the case of MMF scores and a decrease for the frontier, on average, as time goes by. Hence, even though the level of industrial environmental efficiency is actually being

[7] Recall that ENE_F, ENE_{MF} and ENE_{MMF} refer to the technology frontier of sectors, countries and Europe respectively.

reduced throughout the sample period, the existence of technological spillovers, diffusion of knowledge, differences in the environmental regulatory schemes and resource/energy use lead to higher levels in Europe.

Table 3: Environmental efficiency scores of industries

Code	ENE_F	ENE_{MF}	ENE_{MMF}	Code	ENE_F	ENE_{MF}	ENE_{MMF}	Code	ENE_F	ENE_{MF}	ENE_{MMF}
A01	1.000	0.440	0.162	C28	0.892	0.557	0.240	J58	0.956	0.941	0.383
	(0.000)	(0.224)	(0.077)		(0.159)	(0.205)	(0.117)		(0.116)	(0.127)	(0.185)
A02	1.000	0.820	0.242	C29	0.894	0.658	0.237	J59-J60	0.913	0.873	0.318
	(0.000)	(0.272)	(0.132)		(0.192)	(0.288)	(0.166)		(0.172)	(0.204)	(0.156)
A03	1.000	0.959	0.255	C30	0.921	0.729	0.241	J61	0.938	0.918	0.374
	(0.000)	(0.141)	(0.190)		(0.166)	(0.241)	(0.169)		(0.150)	(0.168)	(0.184)
B	0.878	0.603	0.205	C31-C32	0.901	0.589	0.247	J62-J63	0.872	0.838	0.372
	(0.251)	(0.304)	(0.149)		(0.155)	(0.228)	(0.149)		(0.180)	(0.199)	(0.148)
C10-C12	0.717	0.360	0.155	C33	0.986	0.689	0.266	K64	0.967	0.966	0.477
	(0.269)	(0.159)	(0.054)		(0.062)	(0.237)	(0.146)		(0.105)	(0.106)	(0.220)
C13-C15	0.780	0.480	0.177	D35	0.844	0.476	0.120	K65	0.943	0.910	0.408
	(0.210)	(0.203)	(0.070)		(0.290)	(0.289)	(0.091)		(0.151)	(0.180)	(0.204)
C16	0.729	0.464	0.157	E36	0.971	0.797	0.187	K66	0.981	0.973	0.482
	(0.217)	(0.213)	(0.055)		(0.131)	(0.261)	(0.135)		(0.077)	(0.086)	(0.217)
C17	0.683	0.490	0.176	E37-E39	0.677	0.441	0.171	L68	1.000	1.000	0.371
	(0.255)	(0.232)	(0.134)		(0.264)	(0.211)	(0.148)		(0.000)	(0.000)	(0.234)
C18	0.890	0.639	0.208	F	1.000	0.824	0.280	M69-M70	0.879	0.875	0.442
	(0.175)	(0.231)	(0.062)		(0.000)	(0.243)	(0.176)		(0.190)	(0.192)	(0.207)
C19	0.882	0.694	0.199	G45	0.669	0.636	0.309	M71	0.782	0.758	0.373
	(0.255)	(0.358)	(0.221)		(0.230)	(0.213)	(0.139)		(0.223)	(0.226)	(0.187)
C20	0.580	0.391	0.151	G46	0.918	0.900	0.327	M72	0.982	0.924	0.372
	(0.256)	(0.200)	(0.081)		(0.179)	(0.191)	(0.118)		(0.063)	(0.152)	(0.201)
C21	0.994	0.929	0.373	G47	0.786	0.779	0.315	M73	0.900	0.893	0.349
	(0.053)	(0.169)	(0.189)		(0.210)	(0.209)	(0.100)		(0.187)	(0.190)	(0.168)
C22	0.714	0.461	0.190	H49	0.400	0.389	0.153	M74-M75	0.910	0.882	0.393
	(0.194)	(0.180)	(0.078)		(0.210)	(0.196)	(0.064)		(0.174)	(0.187)	(0.181)
C23	0.534	0.317	0.146	H50	0.872	0.664	0.121	N	0.701	0.693	0.289
	(0.190)	(0.078)	(0.045)		(0.258)	(0.344)	(0.057)		(0.236)	(0.241)	(0.136)
C24	0.537	0.405	0.131	H51	0.674	0.334	0.116	O84	0.859	0.852	0.266
	(0.274)	(0.258)	(0.114)		(0.325)	(0.190)	(0.032)		(0.203)	(0.204)	(0.185)
C25	0.790	0.415	0.202	H52	0.495	0.474	0.179	P85	0.991	0.986	0.472
	(0.196)	(0.093)	(0.066)		(0.244)	(0.228)	(0.102)		(0.059)	(0.071)	(0.220)
C26	0.941	0.711	0.286	H53	0.867	0.778	0.262	Q	0.868	0.863	0.375
	(0.155)	(0.248)	(0.146)		(0.213)	(0.253)	(0.130)		(0.220)	(0.223)	(0.194)
C27	0.877	0.583	0.246	I	0.574	0.568	0.246	R_S	0.540	0.533	0.248
	(0.160)	(0.196)	(0.118)		(0.229)	(0.226)	(0.082)		(0.187)	(0.185)	(0.093)

Note: Standard deviation in parentheses

The environmental efficiency scores of the employed industries are displayed in Table 3. When comparing industries into their sectoral technology frontier, high levels of efficiency are evident. On average, the industries of Crop and animal production (A01), Forestry (A02) and Fishing (A03), from the agriculture sector, Basic pharmaceutical products (C21), Repair (C33) and Construction (F), from the manufacturing sector, and Real estate (L68), Scientific research (M72) and Education (P85), from the service sector, are the most efficient from 2000 to 2014. Conversely, Chemicals (C20), Non-metallic products (C23), Basic metals (C24) and Land Transport (H49), Warehousing(H52) and Other Service activities(R_S) are the least environmentally efficient. For example, the industry of basic metals could become environmentally efficient if its inputs and carbon emissions could be reduced by 53.4%. Overall, 35 out of 54 industries (64.8%) exhibit scores higher than the average while only four of them have a score of unity, implying that they are located at the sectoral frontier of best practice.

However, as displayed in Fig. 1 under the frontier concept, industries compete with each other explicitly on the boundaries of sectors, namely agriculture, manufacturing and service sector. In this sense, industries that are efficient into their sector and country, might become inefficient when they will be compared with others outside of their economy. Thus, the exclusion of technological heterogeneity from the analysis may lead to overestimated scores for industries. Under the metafrontier, the results reveal that the levels of environmental efficiency are diminished for the whole set of industries. Overall, 29 out od 54 industries (53.7%) present scores above average. Fishing (A03), Basic pharmaceutical products (C21), Water collection (E36), Construction (F), Activities auxiliary to financial services (K66), Real estate (L68) and Education (P85) industries are the most efficient, albeit the reduction in their scores. In contrast, the industries of Crop and animal production (A01), Food and Beverages (C10-C12), Chemicals (C20), Non-metallic products (C23), Land transport (H49), Air transport (H51) and Warehousing (H52) possess the lowest average values from 2000-2014.

When the meta-metafrontier concept is taken into consideration, environmental efficiency scores divulge the importance of technological heterogeneity among industries. Only 22 out of 54 industries (40.7%) are above average, indicating a sharp decrease on the percentage of efficient industries. More precisely, the industry of Fishing (A03), Basic pharmaceutical products (C21), Computer products (C26), Construction (F), Financial service activities (K64), Activities auxiliary to financial services (K66) and Education (P85) demonstrate the highest average values in each sector. Contrary to the results, in a similar environmental study, Ezici et al. (2020) estimated the eco-efficiency of U.S. manufacturing industries and found that both Food and Chemicals industries are eco-efficient. Shao et al. (2019) showed that the non-metallic products had the highest positive change of eco-efficiency among 36 Chinese sub-sectors while Stergiou and Kounetas (2022) revealed that chemicals and non-metallic products are among the least eco-efficient industries in the European manufacturing sector. Energy-intensive and polluting industries such as mining and metal tend to exhibit lower efficiency scores while others have not made yet the appropriate changes in industrial technology and equipment (Zhang and Song, 2021). Furthermore, different regulatory policies, pollution standards and charges in European countries can improve the environmental efficiency of industries, provided that these are not excessively intensive and be transformed into burden for the industrial environmental protection (Shao et al., 2019).

4.2 Technology Gap Ratio

The technology gap ratio of environmental efficiency is further calculated according to Eqs. 10 and 11. Figure 3 and Table 4 display a comparison of the two TGRs. TGR_1 which measures the distance of the frontier and the metafrontier presents higher values than the TGR_2 that measures the distance of the metafrontier and the meta-metafrontier. This indicates that the heterogeneity of the production technology is smaller between the sectoral and the national frontier and greater between the national and the European frontier. Thus, industries could ameliorate their environmental performance with higher velocity if measures are being set on the basis of the industrial sectors rather than on countries.

Figure 3: Boxplots of TGR_1 and TGR_2

More precisely, Table 4 shows the summary statistics of the sectoral and national ENE and the specific TGR score (TGR_1) for each group. Industries present high environmental efficiency scores within their respective group technologies (sectors). Agriculture technology displays the lowest variation of all group technologies, indicating a higher degree of homogeneity for industries within this sector. Conversely, industries of the service sector are identified as those with the highest degree of variation. The number of industries in each sector results in these differences of variation for each technology. As expected, when comparing industries with respect to the metafrontier technologies, the mean scores decreased at a large extent. The average TGR value of the service sector is the largest one, implying that the technology gap-distance-between the metafrontier and the group frontier is the smallest whilst the TGR of the manufacturing presents the smallest value, indicating a larger technology gap and potential room for improvement at 30% on average. That is to say, the service industries are the leaders and the earliest implementers of environmental technology reform as it is easier for them to adapt their technology and management systems related to environmental protection in the current conditions of the sector.[8]

Table 4: Environmental efficiency estimates (ENE_{MF} and ENE_{F}) and technological gap ratio (TGR_1) with reference to sectors

Sector	Mean	Std.Dev.	Min	Max
Agriculture				
ENE_{MF}	0.758	0.304	0.155	1.000
ENE_{F}	1.000	0.001	1.000	1.000
TGR	0.758	0.304	0.155	1.000
Manufacturing				
ENE_{MF}	0.563	0.275	0.096	1.000
ENE_{F}	0.812	0.246	0.118	1.000
TGR	0.701	0.240	0.163	1.000
Service				
ENE_{MF}	0.791	0.261	0.133	1.000
ENE_{F}	0.821	0.249	0.141	1.000
TGR	0.965	0.119	0.136	1.000

Besides the technology gap between the sectoral and national frontier, the examination of that between national and European technology is also essential, as shown in Table 5. On average terms, industries from Denmark, Croatia and Hungary exhibit the lowest environmental efficiency scores within the national frontier. In contrast, industries from Estonia, Slovakia and Great Britain display the highest values. However, as already mentioned, the examination of efficiency levels within their national boundaries allows the comparison of industries with peers solely from their country. When the European technology comes into play, industries are able to compare with others across Europe. In this way, industries are benchmarked relative to peers that operate under a common, unified technology frontier and technology gap ratios between each country and the European frontier can be estimated.

[8]The nonparametric Kruskal–Wallis test method was adopted to examine whether environmental efficiencies in different groups have significant differences. The null hypothesis is rejected, hence, the environmental efficiency of each group is indeed significantly different.

Table 5: Environmental efficiency estimates (ENE_{MMF} and ENE_{MF}) and technological gap ratio (TGR_2) with reference to European countries

Country	Variable	Mean	Std.Dev.	Min	Max	Country	Variable	Mean	Std.Dev.	Min	Max
AUT	ENE_{MMF}	0.233	0.149	0.068	1.000	HUN	ENE_{MMF}	0.591	0.232	0.171	1.000
	ENE_{MF}	0.765	0.248	0.308	1.000		ENE_{MF}	0.804	0.242	0.302	1.000
	TGR	0.313	0.157	0.079	1.000		TGR	0.749	0.196	0.171	1.000
BEL	ENE_{MMF}	0.185	0.078	0.065	0.623	IRL	ENE_{MMF}	0.293	0.210	0.069	1.000
	ENE_{MF}	0.715	0.268	0.240	1.000		ENE_{MF}	0.694	0.293	0.202	1.000
	TGR	0.268	0.070	0.097	0.623		TGR	0.437	0.210	0.094	1.000
BGR	ENE_{MMF}	0.222	0.132	0.066	1.000	ITA	ENE_{MMF}	0.263	0.209	0.068	1.000
	ENE_{MF}	0.606	0.322	0.130	1.000		ENE_{MF}	0.638	0.300	0.214	1.000
	TGR	0.400	0.136	0.120	1.000		TGR	0.406	0.180	0.081	1.000
CYP	ENE_{MMF}	0.297	0.181	0.080	1.000	LTU	ENE_{MMF}	0.241	0.103	0.072	0.836
	ENE_{MF}	0.684	0.310	0.139	1.000		ENE_{MF}	0.709	0.258	0.217	1.000
	TGR	0.461	0.181	0.110	1.000		TGR	0.351	0.096	0.078	0.836
CZE	ENE_{MMF}	0.308	0.153	0.042	1.000	LUX	ENE_{MMF}	0.237	0.134	0.037	1.000
	ENE_{MF}	0.667	0.281	0.174	1.000		ENE_{MF}	0.691	0.283	0.171	1.000
	TGR	0.484	0.158	0.042	1.000		TGR	0.347	0.106	0.170	1.000
DEU	ENE_{MMF}	0.275	0.177	0.059	1.000	LVA	ENE_{MMF}	0.225	0.143	0.062	1.000
	ENE_{MF}	0.668	0.307	0.138	1.000		ENE_{MF}	0.603	0.298	0.173	1.000
	TGR	0.431	0.171	0.077	1.000		TGR	0.402	0.162	0.115	1.000
DNK	ENE_{MMF}	0.341	0.185	0.075	1.000	MLT	ENE_{MMF}	0.355	0.202	0.125	1.000
	ENE_{MF}	0.682	0.283	0.119	1.000		ENE_{MF}	0.725	0.264	0.257	1.000
	TGR	0.514	0.157	0.142	1.000		TGR	0.505	0.203	0.125	1.000
ESP	ENE_{MMF}	0.222	0.125	0.034	1.000	NLD	ENE_{MMF}	0.238	0.139	0.071	0.883
	ENE_{MF}	0.640	0.289	0.168	1.000		ENE_{MF}	0.698	0.274	0.221	1.000
	TGR	0.360	0.119	0.091	1.000		TGR	0.343	0.123	0.099	0.883
EST	ENE_{MMF}	0.221	0.113	0.072	0.894	POL	ENE_{MMF}	0.300	0.164	0.061	1.000
	ENE_{MF}	0.578	0.311	0.155	1.000		ENE_{MF}	0.657	0.311	0.141	1.000
	TGR	0.429	0.139	0.092	0.894		TGR	0.488	0.168	0.066	1.000
FIN	ENE_{MMF}	0.232	0.129	0.038	1.000	PRT	ENE_{MMF}	0.197	0.123	0.017	1.000
	ENE_{MF}	0.707	0.303	0.144	1.000		ENE_{MF}	0.670	0.300	0.153	1.000
	TGR	0.339	0.108	0.093	1.000		TGR	0.317	0.135	0.047	1.000
FRA	ENE_{MMF}	0.256	0.150	0.033	1.000	ROU	ENE_{MMF}	0.227	0.126	0.057	1.000
	ENE_{MF}	0.755	0.259	0.262	1.000		ENE_{MF}	0.669	0.320	0.096	1.000
	TGR	0.342	0.137	0.055	1.000		TGR	0.386	0.168	0.068	1.000
GBR	ENE_{MMF}	0.282	0.178	0.062	1.000	SVK	ENE_{MMF}	0.161	0.075	0.024	0.489
	ENE_{MF}	0.695	0.278	0.182	1.000		ENE_{MF}	0.682	0.300	0.143	1.000
	TGR	0.405	0.147	0.103	1.000		TGR	0.258	0.097	0.064	0.511
GRC	ENE_{MMF}	0.334	0.221	0.061	1.000	SVN	ENE_{MMF}	0.168	0.085	0.067	0.833
	ENE_{MF}	0.694	0.317	0.125	1.000		ENE_{MF}	0.677	0.280	0.213	1.000
	TGR	0.502	0.206	0.136	1.000		TGR	0.262	0.083	0.090	0.833
HRV	ENE_{MMF}	0.259	0.141	0.074	1.000	SWE	ENE_{MMF}	0.343	0.183	0.054	1.000
	ENE_{MF}	0.716	0.303	0.206	1.000		ENE_{MF}	0.674	0.290	0.134	1.000
	TGR	0.384	0.144	0.110	1.000		TGR	0.543	0.198	0.072	1.000

Hence, industries from Belgium, Slovenia and Slovakia display the lowest values, on average, with respect to the European technology frontier whilst these from Hungary, Malta and Sweden the highest scores. Because of the fact that a proportionally larger share of the pollution-intensive industries are located in the developed countries, there are higher levels of pollution which makes it even more difficult to mitigate their effect and reach the optimal degree of environmental efficiency. However, as the pollution haven effect/hypothesis states, regulatory stringency in developed countries shifts polluting industries to the developing world (Levinson and Taylor, 2008), turning those countries into pollution havens. For example, firms belonging in petroleum and gas, mining, chemicals, steel and other metals, pulp, automobile and airline industries which are characterized as pollution intensive,because they are more sensitive to the change of environmental regulation intensity than other industries would choose to relocate in countries or regions with lax environmental regulations (Wang et al., 2011; Zeng and Zhao, 2009; Dou and Han, 2019). Nevertheless, as Kellenberg (2009) pointed out, other 'non-dirty' industries, such as electronic and appliance manufacturers could also be affected by these policies and be forced to relocate elsewhere.[9]

In terms of the technology gap, industries from Austria, Netherlands and Slovenia demonstrate the lowest scores whilst these from Hungary, Latvia and Ireland the highest ones. The results indicate that the distance between the group frontier and the MMF decreased and environmental technology heterogeneity has been diminished for the industries located in the latter countries. Similar studies showed that Scandinavian and central European countries tend to display better environmental performance than the western and eastern European countries (Ríos and Picazo-Tadeo, 2021). When comparing only western and eastern EU countries, the former present higher environmental efficiency scores than the latter because of the low levels of technology implementation (Vlontzos et al., 2014; Valadkhani et al., 2016; Sanz-Díaz et al., 2017). In this respect, it is essential to underline the EU emissions trading system's (EU ETS) magnitude towards the reduction of greenhouse gas emissions cost-effectively. The installations covered by the ETS reduced emissions by about 35% between 2005 and 2019 in light of heavy fines (EC, 2021).[10] However, when an agreement of emission reduction is reached, the risk of CO_2 leakages[11] gives a comparative advantage to the less energy-intensive industries because of the lower energy/environmental costs that they are dealing (Zofio and Prieto, 2001). To deal with the problem and safeguard the competitiveness, EC has published a list of industries, mainly from the manufacturing sector,[12] that need to receive a higher share of free allowance to confront the problem of carbon leakage. For instance, the importance of the ETS is apparent in the study

[9]However, empirical findings on pollution havens are relatively controversial or there is weak evidence for their existence (Zhen and Shi, 2017).

[10]The EU ETS covers mainly carbon dioxide from the energy-intensive industries, commercial aviation and electricity and heat generation, nitrous oxide and perfluorocarbons from production of aluminium.

[11]Carbon leakage refers to the situation that may occur if firms were to transfer production to other countries with laxer emission constraints due to costs related to climate policies.

[12]`https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014D0746&from=EN`

of Brännlund et al. (1998) who showed that the Swedish pulp and paper industry would have had up to 6% higher profits if the emissions trading had been applied instead of individual permits to achieve the global emissions target.

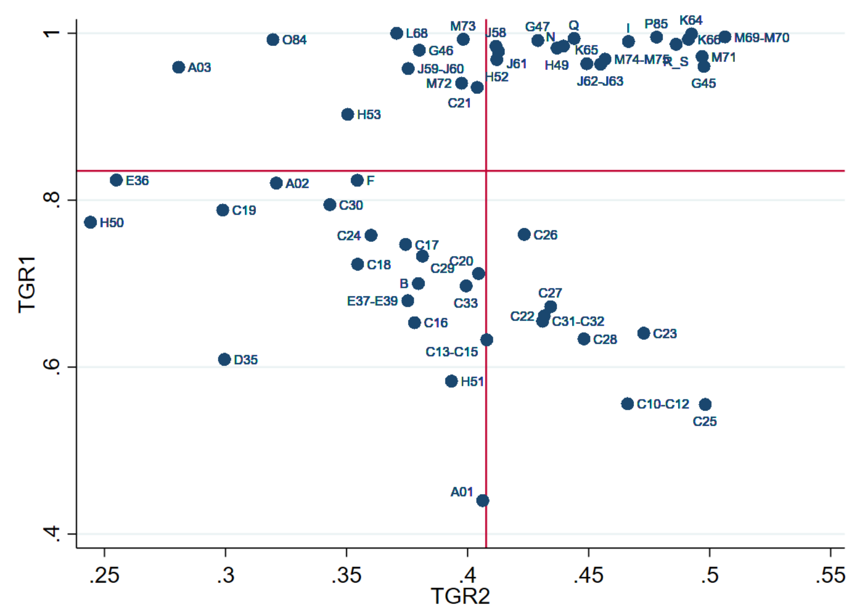

Figure 4: Scatterplot of Technology Gap Ratios

Figure 4 demonstrates the scatterplot of technology gap ratio between the sectoral and the national frontiers (TGR_1) and the technology gap ratio between national and European frontier (TGR_2) for the employed industries. It is apparent that a great number of industries from the service sector is situated in the first quadrant presenting high levels of both TGR_1 and TGR_2. This indicates that they are closer to the available technology in both cases, closing the gap between the sectoral-national and national-European frontier and decreasing the levels of heterogeneity among them. Furthermore, green investment would augment technological innovation capabilities and eventually enhance the environmental efficiency levels (Zhang and Song, 2021). In the second quadrant, there are nine industries in total, most of them belonging to the service sector and two from the agriculture and manufacturing sector. The specific industries present low levels of heterogeneity within their sectoral and national group and high levels within their national and European frontier. Thus, it is apparent that for these 9 industries, technological progress and knowledge diffusion from other industries of the same sector has weakened their differences and led to a faster convergence among them. Conversely, as TGR_2 indicates, national characteristics did not enhance their environmental efficiency scores at the same level. Moreover, only 7 industries from the manufacturing sector are apparent in the fourth quadrant, demonstrating high level of TGR_1 and low level of TGR_2. Finally, the majority of industries are concentrated on the third quadrant, displaying high levels of heterogeneity in all frontier cases.

5 Conclusions

Environmental problems have attracted a lot of attention and created much interest towards the fulfillment of sustainability goals. Improving environmental performance has become a key aspiration of local governments and global societies while it has been considered as one of the most efficacious ways to reduce CO_2 emissions and promote economic development. Thus, the mitigation of the emission of greenhouse gases into the atmosphere is of paramount importance for environmental policies and legislation in European countries.

In this paper, a non-radial environmental performance index, namely ENE, is constructed by considering the utilization of inputs for the production of both desirable and undesirable outputs simultaneously. The incorporation of metafrontier approach into the DDF method enables the examination of environmental efficiency by taking into account the heterogeneity that may exist between different groups. The main objective is to investigate the capability of European industries in 'absorbing' the available technology among sectors or countries and eventually improve their performance. The indicators are empirically estimated for a sample of 54 European industries from all sectors across 28 countries over the 2000-2014 period.

The empirical results clearly reveal significant levels of sectoral and national heterogeneity in European industries. When comparing them solely within their distinct sectors, they display high levels of environmental efficiency. Nevertheless, the estimations may be quite biased as the existence of heterogeneity is not taken under consideration. Therefore, the incorporation of the metafrontier framework enables the technology gap ratio estimation among the different sectors, countries and Europe in general. Environmental efficiency scores are decreased sharply while approximately half of industries present scores above average. The results divulge that improvements in technological process and knowledge diffusion are necessary to reduce the technology gap by using greener research and development procedures, more environmental friendly policies and capital investments in some cases of manufacturing industries and countries.

The aforementioned results could provide European policymakers with practical information for the enhancement of industrial environmental performance. The great differences among groups of sectors and countries should constitute a red alert for European Commission in order to harmonize legislation and determine the most appropriate environmental policies for European members. In this regard, the implementation and promotion of heterogeneous policies among sectors and countries are necessary to achieve the mitigation emissions level.

Finally, possible further research for this study is the examination of the driving factors of environmental performance, such as the effects of policy measures, the implementation of green technologies and environmental research and development, as well as various socioeconomic determinants. Lastly, scenario-based analysis could help policymakers with additional information on environmental efficiency of sectors and European countries. Nonetheless, this paper could become a reliable tool for policymakers and governments and pave the way for future research on sustainability.

Acknowledgments

The author would like to express her sincere gratitude to Konstantinos Kounetas for his insightful comments and suggestions that helped to substantially improve this work.

Appendix

Table A1: List of industries across sectors

Code	Description	Code	Description	Code	Description
Agriculture sector		C27	Electrical equipment	I	Accommodation and food service
A01	Crop and animal production	C28	Machinery and equipment n.e.c.	J58	Publishing activities
A02	Forestry and logging	C29	Motor vehicles, trailers and semi-trailers	J59-J60	Programme and music publishing activities
A03	Fishing and aquaculture	C30	Other transport equipment	J61	Telecommunications
Manufacturing sector		C31-C32	Furniture; other manufacturing	J62-J63	Computer programming, consultancy
B	Mining and quarrying	C33	Repair and installation of machinery	K64	Financial service activities
C10-C12	Food, beverages and tobacco products	D35	Electricity, gas and air conditioning supply	K65	Insurance, reinsurance and pension funding
C13-C15	Textiles and leather products	E36	Water collection, treatment and supply	K66	Activities auxiliary to financial services
C16	Wood and products of wood	E37-E39	Waste collection and disposal activities	L68	Real estate activities
C17	Paper and paper products	F	Construction	M69-M70	Legal and accounting activities
C18	Printing and reproduction of recorded media	***Service sector***		M71	Architectural and engineering activities
C19	Coke and refined petroleum products	G45	Wholesale and retail trade	M72	Scientific research and development
C20	Chemicals and chemical products	G46	Wholesale trade, except of motor vehicles	M73	Advertising and market research
C21	Basic pharmaceutical products	G47	Retail trade, except of motor vehicles	M74-M75	Other professional and technical activities
C22	Rubber and plastic products	H49	Land transport and transport via pipelines	N	Administrative and support service activities
C23	Other non-metallic mineral products	H50	Water transport	O84	Public administration and defence
C24	Basic metals	H51	Air transport	P85	Education
C25	Fabricated metal products	H52	Warehousing	Q	Human health and social work activities
C26	Computer, electronic and optical products	H53	Postal and courier activities	R_S	Other service activities

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