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Non-Parametric Computational Measures for the Analysis of Resource Productivity

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Abstract: In this study, we assumed that 28 European countries (Decision Making Units (DMUs)) aimed to accomplish higher economic outputs, using fewer resources and producing fewer emissions in the form of environmental degradation. In this context, we studied the drivers of total factor productivity change (TFPCH) in DMUs, associated with either managerial capabilities (efficiency change (EC)) or innovations (technical change (TC)) in resource-saving production methods, before and after the integration of CO_2 (carbon dioxide) emissions as an additional variable (undesirable output) in the initial model of one output (gross domestic product (GDP)) and five inputs (labor, capital, energy, domestic material consumption and recycled municipal waste). The primary focus of this study is to identify best practices that policymakers can adopt as they attempt to reduce productivity loss. Our results highlight the weak areas of individual countries and seem to indicate the action that should be taken to improve their productivity by taking into consideration the main driving force behind productivity and technical efficiency change. Our findings reveal that an effective use of technological developments is determined as important strategic information for ensuring managerial performance.

Keywords: total factor productivity; sustainable development; energy use; CO_2 emissions; biomass; recycled municipal waste

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1. Introduction

Resource productivity related to material and energy flow analysis is an important analytical challenge of international environmental economics and policy. Among dynamic approximations with the objective of quantifying the evolution of productivity over a period of time, there is an extensive body of methodological innovations to characterize network data envelopment analysis (DEA) models [1,2] and dynamic changes in productivity when the data of the evaluated DMUs are panel data of multiple periods [3–11]. Such methodological innovations are addressed through the prism of the window analysis framework which is based on the moving average principle [12–14], and the Malmquist index that evaluates the dynamic changes of productivity in two periods [15,16].

In this study, we applied non-parametric computational measures for the analysis of resource productivity based on Malmquist and Malmquist–Luenberger models. It is noteworthy here that some non-parametric applications to estimate the performance of different DMUs in the presence of undesirable outputs or material and energy flows is one of the most notable advancements which has attracted considerable attention. Table 1 contains representative literature on the specific research topics.

The main contribution of this paper lies in the fact that new parameters (i.e., recycled municipal waste) are taken into account in DEA-based models to provide valuable managerial insights into resource productivity, and thus, sustainable development. In terms of resource productivity, tied with the prevention of waste creation and loss, there is a need for a more accurate approach to planning sustainable development paths. This study mainly aims to enrich the existing literature on the nonparametric productivity indices by providing additional evidence that deals with material and energy flow management in European countries. Furthermore, the study points out the delineation of the objectives to be achieved by individual countries and indicates the pathways for inefficient countries to help them improve their efficiency.

Table 1. Methodology and input/output factors used in the previous studies.

Author	Data Sample/Time Interval	Method	Variables (Inputs–Outputs)
Mirmozaffari et al. [17]	Cement companies/2015–2019	Machine learning algorithms, DEA models	Input: energy consumption Intermediate products: cement production, pollution control investment Outputs: waste material removed, waste gas removed, solid waste removed
Wang and Wang [18]	Chinese industry/2011–2016	DEA	Inputs: capital, labor, energy Outputs: industrial output value, CO_2 emission
Shen et al. [19]	15 provinces in the tropics and subtropics of China/2005–2016	DEA	Inputs: ecological footprint, capital stock, labor force Output: Human Development Index
Wang et al. [20]	37 industrial sub-sectors in Liaoning province/2003–2012	DEA, Malmquist–Luenberger Productivity Index	Inputs: fixed assets, labor force, energy consumption Desirable output: added value Undesirable output: CO_2 emissions
Savović and Mimović [21]	Acquired companies in the cement industry/2000–2018	DEA Window analysis, Malmquist Productivity Index	Inputs: material, capital, labor Output: operating revenues
Piao et al. [22]	30 provinces in China/2005–2014	DEA, Malmquist–Luenberger Productivity Index	Inputs: employment, annual water consumption, capital stock, energy consumption Desirable output: GDP Undesirable output: CO_2, SO_2, waste water produced, solid wastes produced
Gao et al. [23]	21 major industrial sectors in China's 30 provinces/2004–2014	DEA, Malmquist Productivity Index	Inputs: capital, labor, energy Desirable output: gross industrial output value Undesirable output: CO_2 emissions
Le et al. [24]	9 East Asian countries/2002–2010	DEA, Malmquist Productivity Index, slacks-based measure (SBM)	Inputs: labor, capital stock, agricultural land, agricultural consumption of fertilizers Desirable output: gross agricultural production value Undesirable output: GHG emissions
Xian et al. [25]	China's power industry/2016–2020	DEA, Luenberger Productivity Index	Inputs: employee, fuel consumption, installed capacity Intended output: gross electricity generation Unintended output: CO_2 emissions
Wang et al. [26]	China's thermal power industry/2006–2014	DEA	Inputs: energy consumption, installed capacity, employee Desirable output: electricity generation Undesirable outputs: CO_2 emission, SO_2 emission, NO_x emission, Soot emission Undesirable output abatements: absorbed SO_2, absorbed NO_x, absorbed soot

Table 1. *Cont.*

Author	Data Sample/Time Interval	Method	Variables (Inputs–Outputs)
Li and Zhang [27]	18 EU countries/1995–2006	DEA	Inputs: capital stock, labor, intermediates (energy, materials and services) Desirable output: gross output Undesirable outputs: CO_2 emissions
Lee [28]	30 provinces in China power sector/2010	DEA	Inputs: Nameplate capacity, labor force, energy consumption Desirable output: electricity Undesirable outputs: CO_2, SO_2, NO_x
Song et al. [29]	30 provinces in China/2006–2013	DEA, Luenberger Productivity Index	Inputs: employees, installed capacity, coal consumption Desirable output: electricity generation Undesirable outputs: CO_2 emissions, SO_2 emissions, NO_x emissions, dust emissions
Bampatsou et al. [30]	EU 15 countries/1995–2011	DEA, Malmquist Productivity Index	Input: total primary energy consumption Desirable output: GDP Undesirable output: CO_2 emissions
Li et al. [31]	17 EU member states/1995–2006	DEA, Sequential Malmquist Productivity Index	Inputs: capital stock, labor, intermediates (energy, materials and services) Desirable output: gross output Undesirable outputs: CO_2 emissions
Nielsen [32]	Iron and steel sector in 14 market economies and 7 planned economies /1973, 1980, 1990 and 2000	DEA	Inputs: coke, iron ore, energy, scrap Outputs: pig iron, crude steel
Rácz and Vestergaard [33]	Danish centralized biogas power plants/1992–2005	DEA, Malmquist Productivity Index	Inputs: animal manure, other organic waste Output: biogas product
Pardo Martínez and Alfonso Piña [34]	Colombian departments in the manufacturing industries/2005 and 2013	DEA, Malmquist Productivity Index	Inputs: energy, labor, capital, materials Desirable output: gross production Undesirable output: CO_2 emissions
Zhou et al. [35]	29 OECD countries/2000–2011	DEA, Malmquist Productivity Index	Inputs: capital stock, labor force Desirable output: gross production Undesirable output: CO_2 emissions, CH_4 emissions, N_2O emissions
Xue et al. [36]	30 provinces in China/2004–2009	DEA, Malmquist Productivity Index	Inputs: coal consumption, electricity consumption Output: industrial value added
Kapelko et al. [37]	Spanish (5706) and Portuguese (965) construction firms/2002–2011	DEA, Luenberger Productivity Index	Inputs: capital, labor, materials Output: operating revenues
Anser et al. [38]	8 world regions/2010–2016	DEA	Inputs: primary energy consumption, total labor force Desirable output: GDP Undesirable output: CO_2, NO_2
Chen et al. [39]	56 Belt and Road Initiative countries/2005–2015	DEA, Malmquist Productivity Index	Inputs: energy consumption, total capital formation, labor Desirable output: GDP Undesirable output: carbon emissions
Mavi and Mavi [40]	OECD countries/2012–2015	DEA, Malmquist Productivity Index	Inputs: labor force, energy use Outputs: GDP, renewable energy, GHG, municipal waste

Notes: OECD: Organization for Economic Cooperation and Development, EU: European Union, GHG: greenhouse gas, CH_4: methane, SO_2: sulfur dioxide, NO_2: nitrogen dioxide, NO_x: nitrogen oxides, N_2O: nitrous oxide.

In this context, we illustrate the application of Malmquist DEA methods to panel data to examine the drivers of total factor productivity change for DMUs under consideration over different time periods. This allows us to decompose the total factor productivity index into its components of technological change (TC—shift on the frontier); technical efficiency change (EC—catching up with their own frontier); pure efficiency change (PEC); and scale efficiency change (SEC) [41,42].

After a brief review of the existing relative literature in Section 1, the structure of the paper is as follows. Section 2 presents the data, the empirical methodology and the formulation of the proposed models. Section 3 provides the empirical findings of the analysis. The final section concludes the paper.

2. Materials and Methods

2.1. Data Analysis: Determining the Total Factor Productivity Change

In our analysis, we determined the index of total factor productivity change and its components by using DEA-based Malmquist (M) and Malmquist–Luenberger (ML) productivity index models (see Table 2) in the case of the 28 European countries (our sample of 28 European countries includes the EU 27 countries as well as the United Kingdom, which officially left the European Union on 31 January 2020), for a period spanning from 2000 to 2018.

Table 2. Variables of DEA-based Malmquist and Malmquist–Luenberger productivity index models.

	M	ML
Outputs	GDP (gdppc)	GDP (gdppc) CO_2 emissions (nCO_2pc)
Inputs	Capital (ck) Labor (emp) Energy (eupc) Biomass (mf2pc) Recycled Municipal Waste (rwastepc)	Capital (ck) Labor (emp) Energy (eupc) Biomass (mf2pc) Recycled Municipal Waste (rwastepc)

As inputs, capital (capital stock at constant 2011 national prices, in million USD, 2011), labor (number of persons engaged, in millions), energy (energy use, in kilograms of oil equivalent per capita), domestic material consumption (biomass, in tons per capita) and recycled municipal waste (tons per capita) were used, while we utilized GDP (GDP per capita, in current USD value) and CO_2 emissions (metric tons per capita) as desirable and undesirable outputs, respectively (see Table 3).

Table 3. Descriptive statistics of variables used in our analysis.

Variable	Obs	Mean	Std. Dev.	Min	Max
gdppc	532	29,026.09	20,606.09	1609.882	118,823.6
nCO_2pc	532	7.5902	3.51785	2.68262	24.8246
ck	532	2,812,413	4,021,601	25,376.45	15,800,000.00
emp	532	8.014896	10.36855	0.1480664	43.62769
eupc	532	3423.755	1451.435	1494.75	9428.812
mf2pc	532	3.768791	1.718302	1.273	10.286
rwastepc	532	145.9269	110.1452	0.0000000001	424.743

The source for capital, labor, GDP and population data was the Penn World Table, version 9.0 [43], and for the energy use, CO_2 emissions, biomass and recycled municipal waste data, the Eurostat resource was used [44].

2.2. The Model for the Determination of Malmquist Productivity Index

The Malmquist Index was first proposed by Malmquist [45] and was further extended by Caves et al. [46] and Färe et al. [16]. In simple terms, this index represents the total factor productivity change between the most recent production point relative to the earlier production point by calculating the ratio of the distances of each data point relatively with a specific regular technology.

Relying on Färe et al. [16], the output-oriented Malmquist productivity index is defined as follows:

$$M = \left[\frac{D_0(x_1, y_1)}{D_0(x_0, y_0)} \times \frac{D_1(x_1, y_1)}{D_1(x_0, y_0)}\right]^{0.5} \quad (1)$$

where M represents the productivity of the most recent production point (x_1, y_1) relative to the earlier production point (x_0, y_0), in relation to a specific common technology. (x_0, y_0) and (x_1, y_1) indicate the previous and the most recent production points, respectively. x denotes the input vector, y denotes the output vector, and D denotes the output distance function. $D_0(x_0, y_0)$ represents the output distance function evaluated at the earlier production point under period 0 technology. $D_1(x_1, y_1)$ represents the output distance function evaluated at the most recent production point under period 1 technology. $D_1(x_0, y_0)$ represents the output distance function evaluated at the earlier production point under period 1 technology. $D_0(x_1, y_1)$ represents the output distance function evaluated at the most recent production point under the period 0 technology.

The M index may be decomposed into technical efficiency (EC) and technological progress (TC) as follows:

$$M = EC \times TC \quad (2)$$

or

$$M = \underbrace{\frac{D_1(x_1, y_1)}{D_0(x_0, y_0)}}_{EC} \underbrace{\left[\frac{D_0(x_1, y_1)}{D_1(x_1, y_1)} \times \frac{D_0(x_0, y_0)}{D_1(x_0, y_0)}\right]^{0.5}}_{TC} \quad (3)$$

The EC index can be further decomposed into pure technical efficiency change (PEC) and scale efficiency change (SEC) as follows:

$$EC = PEC \times SEC \quad (4)$$

Therefore, the M index can be decomposed into the three components:

$$M = PEC \times SEC \times TC \quad (5)$$

or

$$M = \underbrace{\frac{D_{v,1}(x_1, y_1)}{D_{v,0}(x_0, y_0)}}_{PEC} \times \underbrace{\frac{\frac{D_{c,1}(x_1,y_1)}{D_{v,1}(x_1,y_1)}}{\frac{D_{c,0}(x_0,y_0)}{D_{v,0}(x_0,y_0)}}}_{SEC} \times \underbrace{\left(\frac{D_{c,0}(x_1, y_1)}{D_{c,1}(x_1, y_1)} \times \frac{D_{c,0}(x_0, y_0)}{D_{c,1}(x_0, y_0)}\right)^{0.5}}_{TC} \quad (6)$$

The first two components determine the performance of a DMU under both CRS and VRS technologies, while the third component (TC) is calculated relative to the CRS technology. The values of the M index and its components (PEC, SEC and TC) can be greater, equal to, or smaller than 1. When the M index is greater (less) than unity, there is an improvement (decline) in productivity. If the M index and its components are equal to 1, the total factor productivity remains unchanged.

2.3. The Model for the Determination of Malmquist–Luenberger Productivity Index

The ML productivity index is employed to measure productivity growth by introducing both desirable (GDP) and undesirable (CO_2 emissions) outputs in the production model. The ML productivity index is constructed and decomposed in a similar way to the abovementioned productivity index of Malmquist. According to Chung et al. [47], the output-oriented *ML* productivity index based on the two periods (from 0 to 1) directional distance function (DDF) is identified as:

$$ML = \left\{ \frac{[1 + \vec{D}_1(x_0, y_0, b_0; y_0, -b_0)]}{[1 + \vec{D}_1(x_1, y_1, b_1; y_1, -b_1)]} \times \frac{[1 + \vec{D}_0(x_0, y_0, b_0; y_0, -b_0)]}{[1 + \vec{D}_0(x_1, y_1, b_1; y_1, -b_1)]} \right\}^{0.5} \tag{7}$$

where *ML* represents the productivity of the most recent production point (x_1, y_1, b_1) relative to the earlier production point (x_0, y_0, b_0), in relation to a specific common technology. (x_0, y_0, b_0) and (x_1, y_1, b_1) indicate the previous and the most recent production points, respectively. x denotes the input vector, y denotes the desirable output, b represents the undesirable (bad) output, and D denotes the output distance function. $\vec{D}_1(x_0, y_0, b_0; y_0, -b_0)$ represents the output distance function evaluated at the earlier production point under period 1 technology. $\vec{D}_1(x_1, y_1, b_1; y_1, -b_1)$ represents the output distance function evaluated at the most recent production point under period 1 technology. $\vec{D}_0(x_0, y_0, b_0; y_0, -b_0)$ represents the output distance function evaluated at the earlier production point under period 0 technology. $\vec{D}_0(x_1, y_1, b_1; y_1, -b_1)$ represents the output distance function evaluated at the most recent production point under period 0 technology.

The *ML* index may be decomposed into technical efficiency (*ECL*) and technological progress (*TCL*) as follows:

$$ML = ECL \times TCL \tag{8}$$

or

$$ML = \underbrace{\frac{[1 + \vec{D}_0(x_0, y_0, b_0; y_0, -b_0)]}{[1 + \vec{D}_1(x_1, y_1, b_1; y_1, -b_1)]}}_{ECL} \underbrace{\left\{ \frac{[1 + \vec{D}_1(x_0, y_0, b_0; y_0, -b_0)]}{[1 + \vec{D}_0(x_0, y_0, b_0; y_0, -b_0)]} \times \frac{[1 + \vec{D}_1(x_1, y_1, b_1; y_1, -b_1)]}{[1 + \vec{D}_0(x_1, y_1, b_1; y_1, -b_1)]} \right\}^{0.5}}_{TL} \tag{9}$$

The *ECL* index can be further decomposed into pure technical efficiency (*PECL*) and scale efficiency (*SECL*) as follows:

$$ECL = PECL \times SECL \tag{10}$$

Therefore, the *ML* index can be decomposed into the three components:

$$ML = PECL \times SECL \times TCL \tag{11}$$

or

$$ML = \underbrace{\frac{1 + \vec{D}_{v,0}(x_0, y_0, b_0; y_0, -b_0)}{1 + \vec{D}_{v,1}(x_1, y_1, b_1; y_1, -b_1)}}_{PECL} \times \underbrace{\frac{\frac{1+\vec{D}_{c,0}(x_0,y_0,b_0;y_0,-b_0)}{1+\vec{D}_{v,0}(x_0,y_0,b_0;y_0,-b_0)}}{\frac{1+\vec{D}_{c,1}(x_1,y_1,b_1;y_1,-b_1)}{1+\vec{D}_{v,1}(x_1,y_1,b_1;y_1,-b_1)}}}_{SECL} \times \underbrace{\left(\frac{[1 + \vec{D}_{c,1}(x_0, y_0, b_0; y_0, -b_0)]}{[1 + \vec{D}_{c,0}(x_0, y_0, b_0; y_0, -b_0)]} \times \frac{[1 + \vec{D}_{c,1}(x_1, y_1, b_1; y_1, -b_1)]}{[1 + \vec{D}_{c,0}(x_1, y_1, b_1; y_1, -b_1)]} \right)^{0.5}}_{TCL} \tag{12}$$

where $\vec{D}_{c,0}$, $\vec{D}_{v,0}$, $\vec{D}_{c,1}$, and $\vec{D}_{v,1}$, represent the directional distance functions under constant and variable returns to scale, in relation to a specific common technology.

The first two components determine the performance of a DMU under both CRS and VRS technologies. Specifically, the *PECL* component in each period is defined with respect to the VRS technology, as the ratio of the own-period distance functions, whereas the *SECL* component in each time period is constructed as the ratio of the distance function from both CRS and VRS frontiers. The third component (*TCL*) is calculated relative to the CRS technology.

Similar to the *M* index, the *ML* index and its components (*PECL*, *SECL* and *TCL*) also show productivity advances if their values are greater than one, and reductions in productivity if the values are less than unity.

3. Results

The Malmquist and the Malmquist–Luenberger productivity scores of the 28 European countries for the period 2000 to 2018 are given in Tables 4 and 5, respectively. As shown in Tables 4 and 5, the productivity scores of the Malmquist index range between 0.359 and 3.856, while the productivity scores of the Malmquist–Luenberger index range between 0.587 and 2.51. According to the annual means of the specific indices, the countries can be divided into two categories based on their productivity growth. The first category includes countries whose mean productivity scores is less than unity. In this case, the slowdown in productivity is linked to the loss in productive performance.

The first category includes Bulgaria, Ireland, Denmark, Luxembourg, Belgium, Spain, the Netherlands, France, Italy, Austria, Germany, Finland, Portugal, Sweden, Greece, the United Kingdom, Cyprus, Malta, and Slovenia, based upon the Malmquist model, and Ireland, Denmark, Luxembourg, Belgium, Netherlands, Austria, Finland, Italy, France, Spain, Sweden, Greece, Germany, the United Kingdom, Cyprus, and Portugal, based upon the Malmquist–Luenberger model.

The second category where the mean productivity scores are greater than unity is directly linked to productivity gains and includes Hungary, Poland, Estonia, Slovakia, Latvia, Czechia, Lithuania, Croatia, and Romania, based upon the Malmquist model, and Malta, Slovenia, Hungary, Poland, Bulgaria, Latvia, Slovakia, Croatia, Czechia, Lithuania, Estonia, and Romania, based upon the Malmquist–Luenberger model.

In the cases of Bulgaria (11.65%), Ireland (0.20%), Belgium (0.17%), Spain (1.24%), Netherlands (0.20%), Italy (0.45%), France (0.63%), Germany (0.59%), Austria (0.07%), Portugal (2.28%), Greece (0.06%), the United Kingdom (0.04%), Cyprus (1.10%), Malta (3.03%), Slovenia (1.19%), Hungary (0.77%), Estonia (5.86%) and Slovakia (1.83%), there is an increase in the TFPCH index after the integration of CO_2 emissions as an additional variable in the initial model.

In the cases of Denmark (−0.12%), Sweden (−0.01%), Poland (−1.49%), Latvia (−2.19%), Czechia (−1.58%), Lithuania (−1.94%), Croatia (−2.86%) and Romania (−8.67%), there is a decrease in the TFPCH index after the integration of CO_2 emissions as an additional variable in the initial model.

In many cases, the differences are due to the advanced use of emission abatement technology indicated by the Malmquist–Luenberger models and serve as a benchmarking target among DMUs. Additionally, the level of industrialization has a significant impact on energy consumption and CO_2 emissions, and therefore on productivity change, which varies among countries with different levels of development and transition to clean energy.

Comparing the productivity scores before (Malmquist model) and after (Malmquist–Luenberger model) the integration of CO_2 emissions as an additional variable, we found that in the cases of Luxembourg (0.00%) and Finland (0.00%), the TFPCH index remained unchanged.

The productivity analysis and the identification of the best practice DMUs with different production mixes to the efficient frontier indicated the flexibility of an inefficient DMU to choose an improvement direction that optimizes energy and material flow management, and thus its productivity.

The decomposition analysis of the TFPCH index on its driving forces was determined as an important strategic information tool for increasing the competitive power of inefficient DMUs, guaranteeing their comparative advantage in the long run (Tables 4–6, Tables A1 and A2 (Appendix A).

Table 4. Malmquist productivity indices.

Country	2000–2001	2001–2002	2002–2003	2003–2004	2004–2005	2005–2006	2006–2007	2007–2008	2008–2009	2009–2010	2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	2016–2017	2017–2018	Mean
Austria	1.043	0.933	0.836	0.921	0.970	0.951	0.852	0.922	1.015	1.077	0.900	1.033	0.968	0.955	1.160	0.980	0.929	0.932	0.965
Belgium	0.989	0.903	0.824	0.871	0.955	0.942	0.885	0.910	1.051	1.059	0.871	1.001	0.977	0.933	1.145	0.954	0.944	0.912	0.952
Bulgaria	1.001	0.854	0.764	0.882	0.809	0.885	0.706	0.868	0.933	1.079	0.925	1.005	0.922	0.981	1.171	0.946	0.950	0.894	0.921
Croatia	1.267	1.059	0.833	1.091	1.098	1.109	0.895	0.859	0.963	1.461	1.642	1.755	0.988	0.997	1.154	0.990	0.927	0.921	1.112
Cyprus	0.990	0.917	0.818	0.843	1.026	0.970	0.962	1.046	1.074	1.004	0.978	1.076	0.912	1.035	1.132	0.923	0.904	0.891	0.972
Czechia	0.942	0.775	0.753	2.459	0.971	1.026	1.051	0.836	1.275	1.093	1.004	1.381	1.041	1.101	1.186	1.117	0.894	0.895	1.100
Denmark	1.017	0.908	0.855	0.848	0.930	0.965	0.878	0.914	1.061	1.032	0.881	1.020	0.956	0.915	1.140	0.947	0.942	0.868	0.949
Estonia	1.421	0.546	1.925	0.873	0.860	0.747	0.923	0.761	1.253	0.878	1.025	0.773	0.898	1.992	1.059	0.921	1.032	0.907	1.044
Finland	0.994	0.966	0.849	0.877	0.963	0.943	0.867	0.878	1.051	1.050	0.968	1.027	0.912	0.986	1.215	0.981	0.925	0.941	0.966
France	1.000	0.938	0.777	0.950	0.950	0.947	0.878	0.923	1.053	1.029	0.898	1.075	0.959	0.958	1.172	0.951	0.954	0.907	0.962
Germany	0.973	0.915	0.779	1.014	0.947	0.930	0.952	0.926	1.043	1.034	0.890	1.066	0.949	0.948	1.157	0.970	0.952	0.928	0.965
Greece	0.983	0.896	0.778	0.859	0.991	0.858	0.868	0.885	1.070	1.058	1.017	1.113	0.912	0.999	1.227	0.998	0.994	0.945	0.969
Hungary	0.895	0.980	0.980	1.221	0.953	0.978	0.801	0.933	1.115	1.073	0.950	1.212	0.911	1.010	1.166	1.016	0.881	0.929	1.000
Ireland	0.961	0.902	0.801	0.892	0.931	0.934	0.882	0.971	1.123	1.068	0.874	1.047	0.939	0.921	0.924	0.968	0.898	0.874	0.939
Italy	0.981	0.925	0.828	0.946	0.989	0.942	0.898	0.899	1.041	1.051	0.906	1.044	0.942	0.958	1.188	0.921	0.929	0.920	0.962
Latvia	1.264	0.919	1.546	1.396	0.737	0.951	0.849	0.913	1.466	1.015	0.906	1.345	1.414	0.982	1.205	0.944	0.913	0.875	1.091
Lithuania	0.997	0.904	0.806	.	0.883	0.889	2.462	0.920	1.149	0.666	2.274	1.121	0.917	0.974	1.177	0.951	0.892	0.879	1.110
Luxembourg	0.932	0.941	0.815	0.945	0.893	0.967	0.851	0.846	1.103	0.990	0.864	1.111	0.835	1.039	1.066	0.974	1.016	0.906	0.950
Malta	1.018	0.782	0.988	0.961	1.105	1.077	0.616	0.858	1.165	1.010	1.251	1.113	0.843	0.872	1.073	0.972	0.950	0.892	0.975
The Netherlands	0.973	0.909	0.819	0.895	0.914	0.930	0.946	0.921	1.070	1.084	0.878	1.087	0.951	0.937	1.143	0.969	0.939	0.856	0.957
Poland	1.170	0.806	0.856	1.201	1.085	1.054	0.865	0.965	1.277	1.018	0.737	1.086	1.096	1.386	1.240	1.065	0.898	0.919	1.040
Portugal	0.987	0.906	0.812	0.908	0.960	0.905	0.882	0.911	1.100	0.990	0.952	1.118	0.950	1.008	1.199	0.959	0.933	0.912	0.966
Romania	2.385	1.042	0.359	2.238	1.124	0.427	0.617	1.331	1.257	3.856	0.779	1.255	0.808	0.929	1.116	0.999	0.967	0.697	1.233
Slovakia	1.039	0.873	0.817	0.886	0.454	1.401	1.226	1.018	1.126	1.097	1.036	1.222	0.784	0.974	1.703	1.444	1.003	0.961	1.059
Slovenia	0.803	1.556	0.841	0.993	0.925	0.884	0.865	0.831	0.981	1.155	1.062	1.041	0.953	0.962	1.137	1.035	0.861	1.012	0.994
Spain	0.960	0.923	0.799	0.883	0.928	0.924	0.873	0.884	1.004	1.037	0.944	1.106	0.943	0.959	1.186	0.995	0.912	0.942	0.956
Sweden	1.126	0.941	0.788	0.900	1.032	0.808	0.904	0.933	1.129	0.959	0.860	1.047	0.945	0.990	1.175	0.975	0.955	0.963	0.968
United Kingdom	1.022	0.952	0.893	0.891	0.966	0.933	0.857	1.053	1.148	0.999	0.878	1.003	0.970	0.866	1.044	1.067	1.010	0.914	0.970

Table 5. Malmquist–Luenberger productivity indices.

Country	200–2001	2001–2002	2002–2003	2003–2004	2004–2005	2005–2006	2006–2007	2007–2008	2008–2009	2009–2010	2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	2016–2017	2017–2018	Mean
Austria	1.042	0.933	0.838	0.921	0.970	0.951	0.852	0.930	1.012	1.071	0.901	1.032	0.970	0.961	1.147	0.993	0.927	0.937	0.966
Belgium	0.988	0.902	0.826	0.870	0.955	0.945	0.895	0.913	1.071	1.057	0.871	0.998	0.977	0.940	1.137	0.943	0.965	0.905	0.953
Bulgaria	1.074	0.932	0.959	0.922	0.986	1.086	1.006	1.186	0.896	1.042	1.169	0.983	1.033	1.175	1.120	1.105	1.014	0.985	1.037
Croatia	1.265	1.056	0.861	1.058	1.106	1.107	1.018	0.952	0.951	1.299	1.506	1.245	1.077	1.033	1.031	1.048	0.944	0.935	1.083
Cyprus	0.974	0.917	0.897	0.832	1.032	1.017	0.987	1.046	1.063	0.961	0.977	1.058	0.925	1.075	1.087	0.995	0.941	0.917	0.983
Czechia	0.942	0.775	0.753	2.194	0.961	1.047	1.083	0.837	1.275	1.039	1.004	1.381	1.079	1.143	1.064	1.165	0.875	0.901	1.084
Denmark	1.017	0.907	0.865	0.842	0.929	0.965	0.878	0.920	1.057	1.028	0.881	1.018	0.967	0.920	1.117	0.951	0.907	0.887	0.948
Estonia	1.119	0.715	2.510	0.852	0.941	0.890	1.256	0.765	1.245	0.949	1.025	0.773	0.898	1.992	1.059	0.921	1.032	0.907	1.103
Finland	0.995	0.966	0.849	0.877	0.963	0.943	0.867	0.878	1.051	1.050	0.968	1.027	0.912	0.986	1.215	0.981	0.925	0.941	0.966
France	1.001	0.931	0.795	0.987	0.920	0.963	0.932	0.937	1.049	1.012	0.917	1.076	0.959	0.965	1.151	0.965	0.962	0.911	0.968
Germany	0.960	0.910	0.768	1.043	0.935	0.938	1.014	0.948	1.045	1.023	0.908	1.066	0.951	0.957	1.151	0.979	0.954	0.930	0.971

Table 5. *Cont.*

Country	200–2001	2001–2002	2002–2003	2003–2004	2004–2005	2005–2006	2006–2007	2007–2008	2008–2009	2009–2010	2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	2016–2017	2017–2018	Mean
Greece	0.975	0.905	0.847	0.850	0.988	0.891	0.936	0.913	1.047	0.987	0.998	1.094	0.934	1.065	1.066	1.031	0.955	0.982	0.970
Hungary	1.040	0.875	0.900	0.970	1.038	1.022	0.973	1.011	1.004	0.991	0.984	0.973	1.096	1.106	1.102	1.112	0.945	1.000	1.008
Ireland	0.961	0.902	0.801	0.888	0.931	0.934	0.897	0.973	1.116	1.062	0.874	1.047	0.942	0.927	0.942	0.973	0.899	0.876	0.941
Italy	0.973	0.928	0.851	0.937	0.983	0.947	0.908	0.917	1.068	1.019	0.933	0.990	0.983	0.997	1.153	0.939	0.929	0.936	0.966
Latvia	1.148	0.965	1.130	1.069	0.964	1.096	1.140	0.977	1.126	0.845	1.080	1.267	1.213	1.092	1.085	1.077	0.989	0.983	1.069
Lithuania	1.007	0.951	0.907	.	0.993	1.023	1.857	1.059	0.971	0.772	1.539	1.090	1.048	1.107	1.131	1.106	0.989	0.980	1.090
Luxembourg	0.932	0.941	0.815	0.945	0.893	0.968	0.852	0.847	1.103	0.990	0.865	1.111	0.836	1.039	1.065	0.974	1.014	0.905	0.950
Malta	1.029	0.739	1.077	0.959	1.041	1.160	0.770	0.922	1.217	0.901	1.243	1.143	0.924	0.956	1.078	1.032	0.968	0.929	1.005
The Netherlands	0.971	0.887	0.806	0.890	0.902	0.946	0.950	0.945	1.073	1.038	0.906	1.096	0.978	0.948	1.139	0.976	0.979	0.828	0.959
Poland	0.942	0.904	0.948	0.919	0.980	1.100	1.009	1.007	1.061	1.048	0.862	1.082	1.174	1.298	1.144	1.091	0.948	0.940	1.025
Portugal	0.962	0.960	0.842	0.898	0.996	0.950	1.015	0.950	1.067	0.928	0.985	1.008	1.089	1.048	1.133	1.045	0.965	0.959	0.989
Romania	1.268	0.991	0.896	2.027	1.277	0.606	0.777	1.502	1.133	1.856	1.038	1.133	1.005	1.049	1.073	1.100	1.030	0.862	1.146
Slovakia	1.130	0.897	0.860	1.033	0.587	1.356	1.224	1.047	1.118	1.075	1.064	1.213	0.869	1.035	1.484	1.480	0.946	0.976	1.077
Slovenia	0.915	1.419	0.920	0.938	0.936	0.936	0.951	0.856	0.810	1.121	1.028	0.924	1.112	1.235	1.028	1.093	0.826	1.065	1.006
Spain	0.961	0.929	0.852	0.884	0.920	0.954	0.931	0.892	0.988	0.998	0.988	1.061	0.989	0.984	1.150	1.044	0.923	0.981	0.968
Sweden	1.122	0.942	0.790	0.900	1.032	0.808	0.904	0.936	1.099	0.972	0.860	1.047	0.956	0.992	1.176	0.975	0.955	0.963	0.968
United Kingdom	1.018	0.949	0.892	0.890	0.967	0.937	0.868	1.056	1.120	0.986	0.908	1.004	0.972	0.874	1.047	1.062	1.007	0.915	0.971

Table 6. Determinants of TFPCH index before and after the inclusion of undesirable output in the initial model.

<table>
<tr><th></th><th colspan="2">TFPCH</th><th colspan="2">The Main Determinants of TFPCH: EC-TC</th><th colspan="2">The Main Determinants of EC: PEC-SEC</th></tr>
<tr><th>Countries</th><th>M</th><th>ML</th><th>M</th><th>ML</th><th>M</th><th>ML</th></tr>
<tr><td>Austria, Belgium, Denmark, France, Germany, Greece, Italy, Portugal, Spain, Sweden, United-Kingdom</td><td colspan="2" rowspan="5">Performance worsening</td><td colspan="2" rowspan="5">Catch-up effect</td><td>Increasing trend in PEC</td><td>Increasing trend in SEC</td></tr>
<tr><td>Finland, Ireland</td><td colspan="2">Increasing trend in SEC</td></tr>
<tr><td>Luxembourg</td><td colspan="2">PEC and SEC are of equal importance</td></tr>
<tr><td>The Netherlands</td><td colspan="2">Increasing trend in PEC</td></tr>
<tr><td>Cyprus</td><td rowspan="3">Increasing trend in SEC</td><td>PEC and SEC are of equal importance</td></tr>
<tr><td>Bulgaria</td><td rowspan="3">Performance worsening</td><td rowspan="3">Performance improving</td><td rowspan="3">Catch-up effect</td><td>Catch-up effect</td><td>Increasing trend in PEC</td></tr>
<tr><td>Malta</td><td>Frontier shift effect</td><td>PEC and SEC are of equal importance</td></tr>
<tr><td>Slovenia</td><td>Catch-up effect</td><td rowspan="5">Increasing trend in PEC</td><td rowspan="3">Increasing trend in SEC</td></tr>
<tr><td>Hungary, Latvia, Lithuania, Slovakia</td><td colspan="2" rowspan="5">Performance improving</td><td rowspan="4">Catch-up effect</td><td rowspan="3">Frontier shift effect</td></tr>
<tr><td>Croatia</td></tr>
<tr><td>Czechia, Romania</td><td>Increasing trend in PEC</td></tr>
<tr><td>Poland</td><td>Catch-up effect</td><td>Increasing trend in SEC</td></tr>
<tr><td>Estonia</td><td colspan="2">Catch-up effect</td><td colspan="2">Increasing trend in PEC</td></tr>
</table>

In Table 6, the profile of each country in terms of energy and material flow management is mapped. From Table 6, we can conclude the following points:

- In the Malmquist model, the primary driving force of productivity change in the whole sample arises as a result of an improvement in technical efficiency;
- In the Malmquist–Luenberger model, the primary driving force of productivity change arises either as a result of an improvement in technical efficiency (Bulgaria, Ireland, Denmark, Luxembourg, Belgium, Spain, the Netherlands, Italy, France, Germany, Austria, Portugal, Finland, Sweden, Greece, United Kingdom, Cyprus, Slovenia, Poland and Estonia) or due to technological progress (Malta, Hungary, Slovakia, Latvia, Czechia, Lithuania, Croatia and Romania);
- In the Malmquist model, the primary driving force of efficiency change is related either to an improvement in pure technical efficiency (Denmark, Belgium, Spain, the Netherlands, Italy, France, Germany, Austria, Portugal, Sweden, Greece, United Kingdom, Slovenia, Hungary, Poland, Estonia, Slovakia, Latvia, Czechia, Lithuania, Croatia and Romania) or to an improvement in scale efficiency (Bulgaria, Ireland, Finland, Cyprus, Malta). In the case of Luxembourg, the driving forces of pure and scale efficiency change are of equal importance;

- In the Malmquist–Luenberger model, the primary driving force of efficiency change is related either to an improvement in pure technical efficiency (Bulgaria, the Netherlands, Estonia, Czechia and Romania) or to an improvement in scale efficiency (Ireland, Denmark, Belgium, Spain, Italy, France, Germany, Austria, Portugal, Finland, Sweden, Greece, United Kingdom, Slovenia, Hungary, Poland, Slovakia, Latvia, Lithuania and Croatia). However, in the cases of Luxembourg, Cyprus and Malta, the driving forces of pure and scale efficiency change are of equal importance.

4. Discussion

In the cases of Austria, Belgium, Denmark, France, Germany, Greece, Italy, the Netherlands, Portugal, Slovenia, Spain, Sweden and the United Kingdom, although improvement in both management and technology factors reflects the achievement of optimal allocation of resources in the production process of DMUs and therefore the improvement in technical efficiency, the overall productivity has remained poor due to the adverse shift in the production frontier that can negatively impact resource conservation and recovery. This implies that resource allocation and resource saving production methods must be based on the perspective of technological progress and innovation to encourage increased throughput of raw materials and energy.

In the cases of Bulgaria, Cyprus, Finland, Ireland and Malta, DMUs' improvement in technical efficiency which results from the improvement in scale efficiency and thus the largest, most productive scale size is expressed by the convergence between their optimal production scale and the actual production scale. However, in contrast to the technical efficiency improvement, the overall productivity has remained poor, which indicates that there is considerable room for targeted knowledge that advanced technologies can create for the production activities of companies and countries. This will help policymakers to develop accurate business investments in order to build a successful strategic business plan of high value-adding technologies and the utilization of local resources.

By contrast, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, which performed the best in terms of overall productivity (productivity gains), experienced a strong efficiency progress due to the achievement of the optimal allocation of resources in the production process. To maintain such significant gains and further boost productivity, the specific DMUs need to enhance the introduction of advanced technologies in key areas (i.e., energy storage) and determine their future impact, by capturing current technical readiness and adoption levels across processes, industries, and geographies.

It is worth noting that after the integration of CO_2 emissions as an additional variable in the initial model, a dispute arose in the majority of the countries analyzed (Denmark, Belgium, Spain, Italy, France, Germany, Austria, Portugal, Sweden, Greece, United Kingdom, Slovenia, Hungary, Poland, Slovakia, Latvia, Lithuania and Croatia), relating to the fundamental driving force (SECL) of technical efficiency, through which the specific countries could manage to reduce the long-term average cost as production increases.

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Appendix A

Table A1. Annual means, for the entire period, of Malmquist productivity index components by country.

Countries	EC	TC	PEC	SEC
Austria	1.0260	0.9411	1.0253	1.0009
Belgium	1.0102	0.9418	1.0085	1.0018
Bulgaria	0.9798	0.9389	0.9872	1.0089
Croatia	1.0629	1.0457	1.0574	1.0084
Cyprus	1.0091	0.9637	1.0000	1.0102
Czechia	1.0540	1.0420	1.0647	0.9713
Denmark	1.0066	0.9420	1.0055	1.0010
Estonia	1.1031	0.9770	1.2303	1.0150
Finland	1.0216	0.9519	1.0115	1.0152
France	1.0151	0.9479	1.0145	1.0004
Germany	1.0225	0.9448	1.0217	1.0015
Greece	1.0269	0.9444	1.0267	1.0012
Hungary	1.0392	0.9666	1.0440	0.9950
Ireland	1.0000	0.9392	1.0000	1.0000
Italy	1.0122	0.9502	1.0097	1.0037
Latvia	1.0945	1.0174	1.0916	1.0653
Lithuania	1.1123	1.0031	1.1360	1.0271
Luxembourg	1.0000	0.9496	1.0000	1.0000
Malta	1.0015	0.9718	1.0000	1.0015
The Netherlands	1.0176	0.9406	1.0132	1.0056
Poland	1.0590	0.9985	1.0645	1.0006
Portugal	1.0235	0.9441	1.0225	1.0024
Romania	1.0925	1.0812	1.0000	0.9351
Slovakia	1.0505	1.0160	1.0522	1.0002
Slovenia	1.0501	0.9526	1.0500	1.0130
Spain	1.0108	0.9458	1.0096	1.0022
Sweden	1.0242	0.9455	1.0123	1.0121
United Kingdom	1.0171	0.9546	1.0133	1.0038

Table A2. Annual means, for the entire period, of Malmquist–Luenberger productivity index components by country.

Countries	ECL	TCL	PECL	SECL
Austria	1.0229	0.9456	1.0047	1.0178
Belgium	1.0092	0.9451	0.9980	1.0115
Bulgaria	1.0254	1.0162	1.0123	1.0114
Croatia	1.0001	1.0829	1.0000	1.0002
Cyprus	1.0000	0.9833	1.0000	1.0000
Czechia	1.0387	1.0465	1.0277	1.0143
Denmark	1.0018	0.9455	1.0000	1.0018
Estonia	1.1309	0.9975	1.0829	1.0268
Finland	1.0216	0.9518	0.9993	1.0221
France	1.0118	0.9585	0.9999	1.0119
Germany	1.0202	0.9527	1.0084	1.0111
Greece	1.0008	0.9716	0.9917	1.0086
Hungary	1.0035	1.0050	0.9943	1.0091
Ireland	1.0000	0.9412	1.0000	1.0000
Italy	1.0066	0.9611	0.9974	1.0090
Latvia	1.0156	1.0533	1.0000	1.0156
Lithuania	1.0352	1.0430	1.0069	1.0316
Luxembourg	1.0000	0.9496	1.0000	1.0000
Malta	1.0000	1.0050	1.0000	1.0000
The Netherlands	1.0119	0.9487	1.0086	1.0029

Table A2. *Cont.*

Countries	ECL	TCL	PECL	SECL
Poland	1.0187	1.0128	1.0035	1.0141
Portugal	1.0053	0.9867	0.9964	1.0080
Romania	1.0003	1.1452	1.0000	0.9987
Slovakia	1.0264	1.0539	0.9968	1.0275
Slovenia	1.0339	0.9914	0.9973	1.0305
Spain	1.0058	0.9653	0.9930	1.0123
Sweden	1.0246	0.9458	1.0000	1.0246
United Kingdom	1.0113	0.9604	1.0025	1.0085

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