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Analysing the Pattern of Productivity Change in the European Energy Industry

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Abstract: For an industry to succeed in a competitive market, it should continuously take care of not only its stakeholders but also its technical efficiency and productivity. In this paper, data envelopment analysis was combined with Malmquist productivity analysis to investigate the pattern of multifactor productivity changes in the European energy industry over the period from 2005–2016. The results showed that the whole industry was technically inefficient and had large potential for improvement. A slight average increase in productivity that was observed over the studied period proved to be sensitive to the financial and economic situation and equally sensitive to technological and efficiency advances. As for efficiency gains, they reflected the nature of the energy industry, implying that they were due to scale efficiencies rather than human resource improvements. Although technological innovation and the optimal scale of production increased productivity, the slow pace at which this occurred and the negative outlook highlighted by the observed trends call for more serious consideration of the future productivity deployment of the European energy industry, particularly in the context of its decarbonisation, diversification, and modernisation.

Keywords: productivity changes; technical efficiency; energy industry; DEA-based Malmquist productivity index; European Union

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1. Introduction

The increasing need for renewables and energy supply diversification as well as for continuous technological progress poses major challenges to the energy sector, which plays an important role in the European economy, directly employing around 1.61 million people and generating around EUR 250 billion in value added, equivalent to the around 4% of value added of the non-financial European Union (EU) business economy [1].

The EU is committed to ensuring energy security, sustainability, and affordability in the context of sustainable development. However, recent studies have shown that the European energy industry faces efficiency problems. Barros and Peypoch [2] and Borozan and Pekanov Starcevic [3] found evidence that energy companies in the EU do not operate at the efficiency frontier, which requires efficiency improvements and necessitates significant changes and structural transformations of the energy system. Transformation is critical to achieving the Paris Agreement targets [4] and the 2050 climate neutrality target set out in the European Green Deal [5], which aims to promote economic growth through the use of green technologies and to support the transition to a low-carbon economy. It also proposes a reduction in greenhouse gas (GHG) emissions to at least 55% by 2030 compared to 1990 levels, which is a significant increase from the 40% target set in the 2030 Climate and Energy Framework [6], as well as achieving the 7th and 3th United Nations Sustainable Development Goals (SDGs) [7]. At the same time, the EU's "Fit for 55 package" will enable the adaptation of current EU legislation to the 2030 and 2050 targets [8]. This will bring remarkable changes in the energy industry.

Increasing the efficiency of the energy industry is extremely important, as it leads to reducing energy costs, maintaining industry competitiveness, and generating revenue to finance investments [9]. Additionally, it leads to an increase in multifactor productivity (hereafter referred to as productivity), which is commonly defined as the ratio between aggregate outputs and aggregate inputs used in the production process. In the last decade, there have been few studies on the efficiency and productivity of the energy industry worldwide [10–12]. However, to the best of our knowledge, there have been no studies analysing productivity changes in the European energy industry. Only its subsectors have been the subject of such analyses [13–15]. This is surprising, especially from a policy point of view, considering that the EU wants to take further steps towards an integrated energy market and a common energy policy.

This paper aims to provide evidence of changes in terms of the multifactor productivity of the European energy industry during the period from 2005–2016, i.e., the period before the powerful institutional changes in the energy industry took place, particularly the Paris Agreement [4], which came into force in 2016, and the Energy Union Strategy [16], which was published in 2015. Following the production function approach and global environmental requirements, productivity changes are considered in a multivariate framework that consists of both desirable and undesirable outputs—revenues and GHG emissions, respectively, and three inputs—labour, investment, and assets. By applying this approach, the paper separates the effects of changes in efficiency from those related to technological changes. It also examines the causes of changes in efficiency, both those related to pure technical efficiency and those resulting from changes in the scale of efficiency.

Data were retrieved from the annual financial reports of the main energy companies in each EU country. Since these companies had an average market share of more than 50% in their countries in 2016 [17] and since many of them have been on the list of the largest European energy companies based on total market capitalization [18,19], these companies are used as a proxy for the European energy industry. The paper first employs data envelopment analysis (DEA) and then Malmquist productivity index (MPI) analysis. The former is a linear programming-based technique that aims to estimate the relative efficiency of the decision-making units (DMUs) operating in the same industry by using multiple inputs to produce multiple outputs [20]. The latter uses mixed-period distance functions to calculate efficiency and productivity changes. The MPI allows researchers to distinguish between technical efficiency changes and technological changes [21]. A decomposition of these components, which relate to both efficiency and productivity changes, can provide insight into the trends and sources of productivity changes in the European energy industry.

The DEA method, originally proposed by Charnes et al. [20], has recently been applied to assess the performance of energy companies (Wu et al. [22] for China; Tavana et al. [23] for Iran; and Borozan and Pekanov Starcevic [3] for the European energy industry). However, these studies failed to consider productivity changes, which seem to be under the influence of turbulent economic times. Understanding the causes of these changes can help energy policy authorities and regulators at EU and national levels to initiate policy measures aimed at ensuring energy availability, increasing energy efficiency, and mitigating climate change.

This paper makes a threefold novel contribution to the literature. First, it considers the changes in productivity in the European energy industry, focusing on their sources–technological innovations and technical efficiency. Second, the paper shows that turbulent economic times have a negative impact on the productivity development path of European energy companies, indicating its procyclical pattern. The changes in efficiency and productivity are manifested along a mild downward trend that is caused by the delayed and inadequate responses of the energy industry to structural changes. Third, this paper provides strong support for the transformation of the European energy industry towards decarbonisation, diversification, and modernisation.

The remainder of this paper is organised as follows: The next section presents the conceptual background explaining multifactor productivity and the main findings from the literature. The second section describes the sample and data as well as the methodology used to calculate the changes in productivity. Section 3 discusses the main findings of the paper, and the last section provides conclusions.

2. Conceptual Background with a Literature Review

Multifactor productivity represents the portion of output that cannot be explained by the totality of inputs used in production and thus indicates the efficiency and intensity of the inputs used [24]. Productivity changes can be divided into two components: change in technical efficiency and technological change, resulting from catching up with best practices and promoting innovation in the technological process, respectively. In addition, the (in)efficiency of companies can result from technical and scale (in)efficiency [25]. Technical efficiency refers to the achievement of maximum output from a given input, while scale efficiency implies the use of an optimal set of inputs. Consequently, technical efficiency refers to achieving best practice in the industry given the technology, while scale efficiency refers to adjusting the scale of operations. Therefore, for a company to increase its total factor productivity, it should increase its efficiency, invest in new technological innovations, or do both.

Productivity in the energy industry has mostly been studied at the country level. For example, Abbot [26] studied multifactor productivity in the Australian electric utility industry, Ramos-Real et al. [27] analysed productivity changes in Brazilian electric utilities, and Liu et al. [11] studied technical efficiency and productivity in Taiwanese energy companies. Specifically, country-level studies tend to be conducted in China (e.g., Song et al. [28], who measured productivity in the Chinese thermal power industry, Lu et al. [12], who analysed and predicted total factor productivity for Chinese petroleum companies, and Zhang et al. [29], who studied multifactor productivity in the Chinese coal industry).

As far as the European energy industry is concerned, there is an obvious lack of studies on productivity. On the one hand, this is surprising given the role of the energy industry in a country. Indeed, the energy industry plays a strategic role in European countries, but it operates below the efficiency frontier [3]. Its high capital intensity should be an important factor contributing to its productivity. However, due to recent changes in energy markets caused by the slow introduction of new, more efficient technologies and practices as well as the shift from manufacturing to service-based industries (i.e., from more energy-intensive to less energy-intensive industries) the profitability of the energy industry has decreased significantly, calling into question its ability to innovate in line with recent increasing economic, social, and environmental demands. On the other hand, energy generation is the largest contributor to anthropogenic GHG emissions. We would therefore expect numerous studies to address this issue.

Few researchers have investigated productivity changes in European energy companies. Barros [30] used DEA and MPI analysis to investigate changes in total productivity on a sample of hydroelectric plants of Portugal Electricity Company and decomposed them into technical efficiency and technological change. He concluded that the firms experienced an average improvement in technical efficiency and technological change, with the latter being higher. Moreover, an increase in scale efficiency was higher than an increase in pure technical efficiency. Lo Storto and Capano [13] analysed productivity changes in the renewable electricity generation sector in Europe over the period from 2002–2011 using DEA and MPI analysis for a sample consisting of companies in the electricity industry in 31 European countries. They found that total productivity was unstable over that period, while technological change contributed to productivity improvements and that efficiency remained stable. Corsatea and Giaccaria [14], while focusing on the electricity and gas sectors of 13 European countries, also found that technological change is the main driver of environmental productivity growth. This was calculated using MPI. They also documented the beneficial effects of market reforms on technical environmental efficiency over the period from 1995–2013. Lu and Lu [31] used DEA to investigate intertemporal efficiency and executive efficiency based on carbon dioxide (CO_2) emissions from fossil fuels in 28 EU countries. They used CO_2 as an undesirable output to analyse its impact on energy efficiency over the period from 2009–2013. Their research mainly reports on intertemporal efficiency. Sanchez-Ortiz et al. [15] studied the efficiency and productivity of five Spanish electricity distribution companies, also using DEA and MPI analysis. They found overall positive efficiency and concluded that overcapacity and tariff deficits have a negative impact on firm efficiency.

One should observe that DEA and the MPI are commonly used approaches to assess efficiency and productivity changes in the energy industry (e.g., [10,27,32]). Certainly, some researchers have used alternative DEA models. For example, Zhang et al. [29] used the super-slack-based measure (Super-SBM) with the MPI to evaluate the total factor productivity of 25 Chinese coal companies. Lu et al. [12] combined three-stage DEA with time series neural networks to evaluate and predict the total factor productivity of 50 Chinese petroleum companies. Finally, Song et al. [28] used DEA and the Malmquist–Luenberger index to evaluate the productivity of the Chinese thermal industry.

To sum up, this paper has pointed out the apparent lack of research regarding efficiency and productivity changes in the energy industry. Although some researchers have studied productivity changes in the European context, to our knowledge, no one has analysed efficiency and productivity changes in the European energy industry. This paper fills this research gap by exploring productivity changes by considering desirable and undesirable outputs. Accordingly, the hypothesis is that the European energy industry experienced only a mild increase in productivity during the period under consideration. We assume that this is primarily a consequence of insufficient technological innovation and a lack of substantial changes in efficiency.

2.1. Sample and Data

The sample consists of 28 EU energy companies that had the largest market share in each member state and that published their financial statements online during the period from 2005–2016. Only three companies were excluded from the initial sample: Ignalinos atomine elektrine (financial statements not publicly available), Twinerg SA (a subsidiary of Electrabel SA, which, in turn, is a subsidiary of GDF SUEZ), and the British Energy Group (acquired by EDF France in 2008). The companies included are part of the electricity industry and are mostly wholly or partially state-owned.

Following the production function approach, three inputs were selected: total assets (representing resources used to generate revenue), the number of employees (representing the total employed workforce), and gross investments (representing investment in new technologies important to the company's future growth), and two outputs: revenue (income generated from the normal operation of the company) and GHG emissions (undesirable output). Total assets, the number of employees, and gross investments have been commonly used as inputs to evaluate the efficiency of energy companies (for the number of employees, see [33,34]; for total assets, see [2]; and for gross investments, see [30]). Regarding GHG emissions, Korhonen and Luptacik [35] found that identifying environmental factors as inputs or outputs does not affect the efficiency frontier. Therefore, we treated GHG emissions as an undesirable output of energy production.

Eurostat was used a data source for the GHG emissions [17], as data thereon were not available in all of the annual financial reports of the included European energy companies. All other data used in DEA analysis were taken from their annual reports.

2.2. Methods

A DEA-based Malmquist productivity index was used to calculate the rates of productivity change. It represents a standard approach to measure and evaluate productivity growth. The calculation process was conducted in two steps; DEA was used in the first step, and Malmquist productivity indices were calculated in the second.

DEA model: Considering the advantages of using DEA, specifically its non-parametric characteristic and its possibility of working with multiple inputs and outputs, the present paper has considered it to be a suitable technique for calculating the technical efficiency scores. Assuming that managers can control inputs more easily than outputs, where a proportional increase in inputs could lead to a disproportionate change in outputs, this paper uses the input-oriented DEA model with constant and variable returns to scale (CRS and VRS, respectively). This type of the DEA model, presented by Model (1), was introduced by Banker et al. [36]. It refers to a situation with K number of inputs, M number of outputs, and n number of DMUs. In this case, for the i-th energy company, x_i stands for a $K \times 1$ vector of inputs and y_i denotes an $M \times 1$ vector of outputs. Moreover, the $(K \times n)$ input matrix X and the $(M \times n)$ output matrix Y represent the data of all n energy companies. The described model is as follows:

$$\begin{gathered} \mathrm{Min}_{\theta,\lambda}\ \theta, \text{ subject to } -y + Y\lambda \geq 0, \\ \theta x_i - X\lambda \geq 0,\ \lambda \geq 0, \end{gathered} \tag{1}$$

where θ refers to the efficiency score of the i-th DMU, and λ is an $n \times 1$ vector of constants.

Banker et al. [36] extended the model developed by Charnes et al. [20] by adding a convexity constraint, $e\lambda = 1$ (e is a $1 \times n$ vector of ones) to account for variable returns to scale. They proposed decomposing the overall technical efficiency into pure technical efficiency and scale efficiency. While the former refers to the ability of management to use given resources efficiently, the latter refers to the ability to exploit economies of scale by operating on the efficiency frontier. The efficiency frontier is constructed as a discrete piecewise linear combination of the most efficient units. Scale efficiency (SE) is presented as the ratio of technical efficiency (TE) to pure technical efficiency (PTE). A DMU is only considered efficient if both $\Theta = 1$ and all associated slack variables in the model equal zero. For more details, see [37].

The Malmquist productivity index (MPI): The MPI, which was empirically implemented by Färe et al. [21] using the DEA method, was used to assess the energy companies' productivity changes over time. It has been extensively applied to measure productivity changes. More specifically, MPI calculates the ratio of the distances the data that are associated with a common technology. The model with constant returns to scale can be stated as follows [21]:

$$MPI_0\left(x^{t+1}, y^{t+1}, x^t, y^t\right) = \left(\frac{D_0^{t+1}\left(x^{t+1}, y^{t+1}\right)}{D_0^t\left(x^t, y^t\right)}\right)\left[\left(\frac{D_0^t\left(x^{t+1}, y^{t+1}\right)}{D_0^{t+1}\left(x^{t+1}, y^{t+1}\right)}\right)\left(\frac{D_0^t\left(x^t, y^t\right)}{D_0^{t+1}\left(x^t, y^t\right)}\right)\right]^{1/2}, \tag{2}$$

where MPI_0 measures the productivity of production points (x^{t+1}, y^{t+1}) relative to the production point (x^t, y^t). The index is calculated by using mixed period technical efficiency scores denoted by $d_0^t\left(x_0^t, y_0^t\right)$ and $d_0^{t+1}\left(x_0^{t+1}, y_0^{t+1}\right)$ in periods t and $t + 1$, respectively, thus using the technology of the period t and the technology of the subsequent period $t + 1$. Since productivity changes can be measured relative to the period t or relative to the period $t + 1$, the MPI is defined as the geometric mean of these two indices. If the value of the MPI exceeds 1, then this indicates a productivity improvement between the periods t and $t + 1$. The inverse case holds for an index value that is less than 1.

The first component (in round brackets) of Expression (2) measures the technical efficiency (TEC) changes over two periods, and the second component (in square brackets) measures the technology (TC) changes over two periods. More precisely, the first component measures whether or not a DMU is approaching its efficiency frontier, while the second component measures whether the frontier is shifting out over time. If the values of any of these components are greater than 1, they indicate improvement. The reverse case holds. If the index is equal to 1, then there are no changes in productivity.

Under the VRS assumption, there is a difference between the CRS distance function and the VRS distance function. Therefore, the changes in technical efficiency are the product of the changes in the pure technical efficiency (PTE), which can be calculated under the assumption of VRS, and the change in scale efficiency (SE), which is a mixture of the CRS and VRS efficiencies. The SE change measures the degree to which a DMU approaches its most productive scale over the period of interest.

Coelli et al. [38] suggest using the Malmquist productivity index based on CRS distance functions, even if the underlying technology exhibits VRS. The reason for this is that productivity change estimates based on VRS distance functions are biased. It is recommended that the VRS distance function only be used to estimate pure technical efficiency and scale efficiency. Therefore, in the first step, we calculated MPI (i.e., the indices TEC and EC) based on CRS; then, in the second step, we further decomposed TEC into PTE change and SE change based on VRS.

3. Empirical Results with Discussion

3.1. Preliminary Analysis

Using the Tukey box plot method, outliers were removed from further analysis because they could have affected the shape of an efficiency frontier, leading to unreliable DEA efficiency results. Two companies were found to be outliers, EDF France and the British Energy Group, possibly because of the size of their businesses. In addition to these two companies, Enel SpA was also found to be an outlier in 2014–2016 due to significant changes in monetary figures. Considering that a calculation of the MPI requires a balanced panel data set and the fact that data were not available from certain energy companies for the period of interest, the final sample was reduced to 19 European companies (Table A1 in the Appendix A).

The process of mean normalisation was performed to eliminate potentially conflicting situations arising from the data, such as different units, scales, and magnitudes (see, [39]). Wang et al. [40] emphasised that this procedure does not affect the efficiency scores obtained by using DEA analysis. Table 1 shows the descriptive statistics of selected outputs (total revenue and GHG emissions) and inputs (total asset, number of employees, and investment) that reveal the heterogeneity within energy companies.

Table 1. Descriptive statistics.

Output/Input	Obs	Mean	Std. Dev.	Minimum	Maximum
Total revenue (in millions of euros at 2015 constant prices)	228	8028.89	12,122.40	67.98	54,422.75
GHG emissions from the energy sector (in millions of tonnes)	228	97.57	175.89	5.79	841.33
Total asset (in millions of euros at 2015 constant prices)	228	20,927.41	28,154.89	1022.45	125,869.62
Number of employees	228	14,017.41	15,987.69	188.00	85,928.00
Investment (in millions of euros at 2015 constant prices)	228	1497.51	2739.71	5.08	16,978.30

The correlation matrix (Table A2 in the Appendix A) shows that there is a significant and positive correlation between the output and input variables. Therefore, the isotonicity property is satisfied, and DEA can be used to estimate the efficiency scores.

3.2. Results with Discussion

Following Coelli et al. [38], both the CRS and VRS scores were calculated, and their results are presented in Figure 1. During the observed period, the technical efficiency score was the highest under CRS in 2007 (0.648), under VRS in 2006 (0.859), and showed scale efficiency in 2007 (0.807). Significant deterioration in technical efficiency scores was observed in the crisis and post-crisis periods. Consistent with this finding, Lo Storto and Capano [13] observed a downward trend in the efficiency of aggregate renewable electricity generation capacity during the period 2002–2011, but they realised that countries with a higher share of installed renewable electricity generation capacity nevertheless experienced an increase in efficiency during the period from 2009–2011. Moutinho et al. [41] also found that technical efficiency scores were lower in most of the 26 European countries observed during the 2009–2012 period, including the financial crisis. Wang and Le [42] provided evidence of the loss of technical efficiency for 17 European countries during 2013–2017. Moreover, their calculated average efficiency score of 0.835 indicates that the EU energy industry was in a worse position than the EU economy as a whole, which also makes technical efficiency a concern. Borozan [43] affirmed that the largest changes in EU-28 productivity over the period from 2000–2018 occurred during the economic crisis. It seems that a mild downward trend in energy efficiency is consistent with the downward trend observed in the European economy.

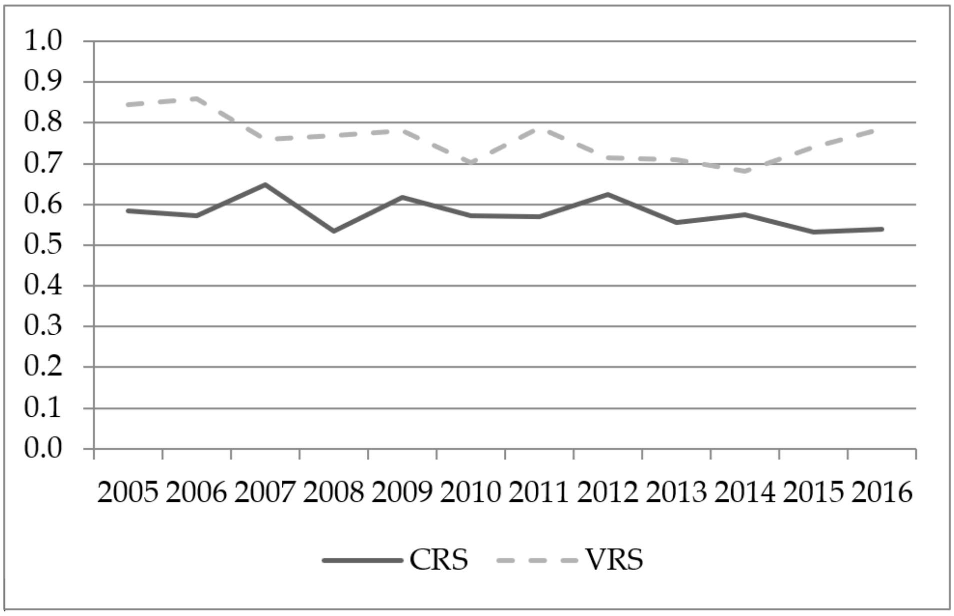

Figure 1. Development of CRS and VRS scores.

European energy industry efficiency decreased at an annual average rate of 0.73% under CRS and by 0.68% under VRS. Only two energy companies are on the efficiency frontier under the CRS assumption and five companies under the VRS assumption in the period considered. Average efficiency scores of 0.577 (under CRS) and 0.761 (under VRS) imply that energy companies could perform better and that scale inefficiency exists (mean scale efficiency score of 0.743). They should improve their performance significantly to reach the efficiency frontier. Although a direct comparison is not possible, as it was not possible in the growth trend case above, it seems that the European energy industry had more room for improvement than the European economy.

Table 2 shows the results of productivity changes decomposed into technical efficiency changes (i.e., pure technical efficiency and scale efficiency change) and technology changes. The MPI changes calculated for the European energy industry as a whole averaged 1.5%, with a low of − 8.4% in the 2008–2009 period and a high of 8.8% in 2006–2007. This average value suggests that the European energy industry only achieved modest productivity growth, while the MPI values indicate that the productivity development path followed a procyclical pattern in the period considered in the present study. Labour productivity procyclicality has already been observed in the EU [44–46] but not at the energy industry level. Looking at the trends, the European energy industry, which is represented by the 19 largest companies, shows a slight downward movement with a compound rate of change of 0.093%. Considering the possible consistency of productivity movements in the energy industry with multifactor or labour productivity of the whole economy, it is worth pointing out the results observed in the literature. Indeed, several authors have found a long-term downward trend in European labour productivity [44,47], suggesting declining competitiveness compared to other advanced economies and emerging markets. Timmer et al. [44] considered the reason for the productivity decline to be the decline of traditional manufacturing but also insufficient investment in technology. Thus, they estimated that labour productivity in the EU-15 fell by 0.7% over the period 2007–2009. From the perspective of the energy industry, whose deterioration in performance after the

2008 financial crisis is particularly striking [48], another reason could be that investments in renewables experienced a sharp decline after a significant increase until 2011. For example, in 2011, they amounted to USD 131.7 billion, and after that year, these investments were significantly reduced, stagnating at around USD 65 billion in 2012–2019 [49]. This is in line with the observations of Lo Storto and Capano [13], who found a growth trend of about 6% on average in renewable electricity generation capacity over the period from 2002–2011. They explained this growth with technological advances rather than efficiency changes.

Table 2. MPI and its components.

Period	Malmquist Productivity Change Index (MPI)	Efficiency Change Index (TE)	Technology Change Index (TEC)	Pure Technical Efficiency Change Index (PTE)	Scale Efficiency Change Index (SE)
2005–2006	1.011	1.086	0.933	1.025	1.058
2006–2007	1.088	0.943	1.156	0.957	0.984
2007–2008	1.079	0.945	1.142	0.943	1.003
2008–2009	0.916	1.131	0.815	1.077	1.050
2009–2010	1.039	1.030	1.013	0.990	1.042
2010–2011	1.045	1.009	1.029	0.982	1.027
2011–2012	1.063	0.972	1.093	0.976	0.995
2012–2013	0.991	1.027	0.969	1.014	1.013
2013–2014	0.944	0.934	1.016	0.954	0.976
2014–2015	0.991	0.975	1.019	0.992	0.983
2015–2016	1.001	1.081	0.931	1.061	1.018
mean	1.015	1.012	1.011	0.998	1.014

Clearly, further research is needed to investigate the relationship between productivity in the European energy industry and the European economy. Furthermore, the differences in productivity between renewables and non-renewables need to be investigated. Indeed, large energy companies differ in terms of their energy mix, which is likely to have an impact not only on their own productivity but also on the productivity of the industry as a whole. Previous research has confirmed that the energy mix, which includes different conventional sources (e.g., coal or gas) and renewables (e.g., hydro, wind, biomass or solar photovoltaic), matters for productivity and growth [50–52] and that creating an optimal energy mix that takes into account productivity and carbon emissions is a critical challenge for the modern world (see [53,54]). Midttun and Piccini [48] have documented that the good performance of the European energy industry only lasted through the first decade of the 21st century. They concluded that only those European energy companies that changed their energy mix to greener and smaller plants did better financially. The issue of energy mix is not addressed in this paper and requires further research.

On average, both components, i.e., technology changes and efficiency changes, contributed almost equally positively to the Malmquist index of the European energy industry. In this context, technical efficiency changes could be attributed to the average scale efficiency changes, with an increase rate of 1.4%, while the average pure technical efficiency changes had a negative impact, indicating moderate efficiency deteriorations in operational and management resources and activities. Given that the energy companies considered here are large companies, it is not surprising that they were able to reach the economies of scale. However, they faced a downward trend in scale efficiency during the period considered, which is also recognised in the literature as a possible cause of technical inefficiency [55]. This adverse trend in the European energy industry can be attributed, among other things, to a decline in final energy consumption from 1041 Mtoe in 2005 to 977 Mtoe in 2016 [56], increasing competition and thus decreasing utilisation capacities, and outdated technologies. The decarbonisation of the EU energy system is also expected to affect the future development and investment of energy companies and will further negatively impact scale efficiency. Indeed, the EU Taxonomy Report (Technical Annex) [57] defines sustainable investments as investments in those energy producers that emit less than 100 gCo2e/kWh. In comparison, highly efficient cogeneration plants emit around 300 g per hour. In this context, new investments in fossil fuel power plants will no longer be financially viable, and energy companies could therefore benefit from diversifying their portfolio from fossil fuels to renewables. Midttun and Piccini [48], who analysed the transformation of the European energy industry from the perspective of the core players in this industry, corroborated these observations.

Management inefficiency, reflected in pure technical efficiency, suggests that European energy companies have not sufficiently invested in the human resource potential of the companies. They face outdated business models and a shortage of human resources, especially, as it can be seen from the results, a shortage of researchers and engineers in the fields of R&D, environment, and quality management. However, they are important for the exploitation of new technologies and for the creation of innovations, know-how, and new green and low-carbon oriented business models (see [58]). Zhen et al. [59] emphasised that neglecting to improve R&D and human capital will have a negative impact on the competitiveness of renewable energy, which argues for investment in human capital development. Insufficient concern for human resources development seems to be related to the privileged position and soft budgeting that energy companies enjoy from being wholly or partially state-owned. Harmful effects of soft budget constraints on technical efficiency of energy companies have been noted by Borozan and Pekanov Starcevic [3], while Du et al. [60] have showed that electricity reforms have a positive impact on the technical efficiency of fossil-fuelled power plants in China. This would imply that state-owned companies could benefit from privatisation by operating in a more competitive market with higher quality management [14,61,62]. The implementation of a new green, digital, and low-carbon oriented business models and management strategies may be beneficial for energy companies (see, e.g, [48,58]).

One factor behind productivity changes in the European energy industry is technological innovation. The industry experienced a slight increase in technological progress and a shift in the best practice frontier, averaging 1.2% over the period considered. Technological innovation in the energy industry is crucial to the transformation of the energy system "to establish energy sustainability, competitiveness and security by 2020 and beyond" [63]. However, according to Sterlacchini [64], electricity companies in the EU reduced their R&D expenditures by 62% during the period from 1990–2004, which was mainly due to privatisation processes that exerted pressure to reduce costs. In addition, EU energy research and innovation budgets were cut by member states, with public sector spending on low-carbon technologies being lower in 2019 than it was in 2012, and member states continued to invest in fossil fuels rather than clean technologies after 2011 [65].

As already mentioned, productivity improvements did not follow a stationary growth rate but exhibited procyclical behaviour. Productivity improvements and losses can be observed in the development path of productivity change. The European energy industry experienced a productivity decline during the crisis period, especially during the financial crisis. A productivity decline during a crisis is not an unusual feature; other authors have already observed a procyclical nature of productivity [43,45,46]. The decline was also recorded in the post-crisis period (2012–2015), which was probably due to the prolonged slowdown and the dramatic decrease in new investments in the energy sector. Investments in Energy Union research and innovation priorities declined significantly after 2011 [65]. In contrast, European energy companies showed the highest productivity changes in the pre-crisis period, i.e., 2006–2007, which was due to technological progress rather than efficiency changes. However, the crises should not be seen as the only cause of the deterioration in the multifactor productivity of the European energy industry. Rather, the crisis periods are sources of short-term cyclical fluctuations that manifest themselves along a long-term downward trend caused by the delayed and inadequate responses of the energy industry and the whole European economy to structural changes.

Although the data for several periods indicate that it is possible to achieve positive changes in efficiency and technology at the same time, it seems that the European energy industry has looked at the issue of technology changes rather than efficiency changes. The improvements in the energy industry, which have already shifted out of the frontier over time, have been initiated by the increased use of new Energy 4.0 technologies. Such technologies, such as smart grids, especially when combined with smart metering, will ultimately further enhance energy security and efficiency.

4. Conclusions

This paper investigated efficiency and productivity changes in the European energy industry. The initial sample comprised 28 EU energy companies over the period from 2005–2016, while the final sample was reduced to 19 companies. Three inputs were selected in the study: total assets, the number of employees, and gross investments. In addition, two outputs were included: revenues and GHG emissions. In the first step of the analysis, the DEA model was used to calculate the technical efficiency scores of the European energy companies, and in the second step, the Malmquist productivity indices were calculated to estimate productivity changes.

The results show an average productivity increase of 1.5% over the observed period, with the lowest value being 8.4% in 2008–2009 and the highest value being 8.8% in 2006–2007. As we hypothesized, the mild average increase in productivity is a consequence of insufficient technological innovation and lack of substantial changes in efficiency. Here, technical efficiency changes are related to the increasing rate of scale efficiency and the decreasing rate of pure technical efficiency. The deterioration of the latter is mainly due to factors related to operational and managerial capabilities, which are possibly caused by the privileged position of state-owned companies. Moreover, productivity changes that follow the changes in the European economy are procyclical. They can be observed in several periods: before, during, and after the crisis. As expected, the highest productivity changes were recorded in the pre-crisis period (2006–2007), which was mainly due to technological progress rather than efficiency changes. The largest decline was recorded at the very beginning of the crisis period. However, a decline was also recorded in the post-crisis period, which was likely due to the prolonged slowdown.

The results suggest that productivity changes reflect the nature and the role of the energy industry. The energy industry is a capital-intensive industry that consists of large companies that create their competitive advantage and added value by continuously investing in technology and by maintaining an optimal scale. However, the industry faces the challenge of a lack of quality management, researchers in R&D, and insufficient energy innovation, which would be the reason for slow progress in terms of future productivity changes and its further lagging behind the productivity of the overall economy. The threat to the future productivity of the European energy industry also comes from unfavourable trends in technological innovation and the maintenance of an optimal scale of production.

Several implications arise from the present results in relation to the decarbonisation, modernisation, and diversification of the European energy industry. Technological innovation should be intensified, particularly in view of the fact that in the post-2011 period countries have continued to invest large amounts of funding for research and innovation in the energy sector in fossil fuels rather than in clean technologies and energies. The fact that the energy sector invests little in research and innovation compared to other sectors will have a negative impact on the EU's efforts to become climate neutral. Therefore, the EU should do more to promote investment in clean technologies if it wants to achieve the SDGs of the UN and the EU's energy and climate policy goals. Moreover, technological innovation in the energy industry is considered an important factor in decoupling energy from the economy and thus minimising the impact of economic activity on environmental quality. Indeed, the decoupling effect of European greenhouse gas emissions is likely to be significantly influenced by technological innovation, especially in the context of greening and low-carbonising the energy industry. This is because green and low-carbon energy sources are seen as a crucial factor in maintaining environmental quality without compromising the achievement of economic goals and quality of life in general at the same time. This paper has not empirically tested the decoupling rate and decarbonisation of the European energy industry. Further research should address these issues. Technological innovation is also at the core of Energy 4.0, which aims to build smart grids, use big data and artificial intelligence, and manage renewable energy. Energy companies have the opportunity to leverage Energy 4.0 in their efforts to build sustainable business models and strategies.

Considering a decreasing trend in economies of scale and increasing competition in energy markets, portfolio diversification should be considered, providing opportunities to achieve the optimal scale of production and to consequently increase investment in clean energy technologies. In addition, the full or partial privatisation of state-owned energy companies could lead them to use more efficient management and to make better use of operational activities. Transformation into private energy producers is also a prerequisite for enabling the separation of energy production and transmission, which is one of the areas of the EU's third energy package that is aimed at improving the internal energy market. By increasing technical efficiency, the energy industry, as an energy producer and consumer, contributes to the decoupling of greenhouse gas emissions from gross domestic product, i.e., from economic activity. However, the need to increase the technical efficiency of the European energy industry is also crucial for the entire European economy, not only because industry should provide competitive energy, but also because this energy should be less carbon intensive. The reduction of harmful emissions, i.e., moving along the downward slope of the environmental Kuznets curve, requires significant changes in the energy industry. The paper suggests that two broad sets of action are needed in terms of technical efficiency. First, there should be a focus on the development of new green, digital, and low-carbon business models and management strategies to create a roadmap for the industry's operations. Second, the size and the scale of operations should be adapted to new green and low-carbon projects.

Future research should also provide a more detailed analysis of the factors influencing productivity trends in the European energy industry and over a broader time frame, with particular attention to the role of government and corporate ownership, distinguishing between renewable and non-renewable energy development paths. A deeper understanding of the determinants of productivity, including the impact of the energy mix, should ensure a solid background for concrete policy proposals aimed at accelerating the process of decarbonisation and modernisation of the European energy industry. The efficiency and effectiveness of individual technological innovations also need to be investigated in order to promote the most promising investments in these processes. Furthermore, the application of alternative methods, such as the Malmquist–Luberger index, could provide new insights in terms of the evaluation of the results obtained in this paper.

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Appendix A

Table A1. EU energy companies included in the sample.

State	Energy Company	State	Energy Company
Austria	VERBUND Hydro Power GmbH	Latvia	Latvenergo
Belgium	GDF SUEZ	Lithuania	Ignalinos atomine elektrine
Bulgaria	Kozloduy NPP Plc	Luxembourg	Twinerg SA
Cyprus	Electricity Authority of Cyprus (EAC)	Malta	Enemalta Corp
Czech Republic	ČEZ Group	The Netherlands	Essent Nederland B.V.
Denmark	DONG Energy	Poland	PGE Polska Grupa energetyczna SA
Estonia	Eesti Energia	Portugal	EDP Producao
Finland	Fortum Power & Heat	Croatia	Hrvatska elektroprivreda d.d.
France	EDF France	Romania	Hidroelectrica
Germany	RWE Power AG	Slovakia	Vodohospodarska Vystavba, s.p.
Greece	PPC Public Power Corp SA	Slovenia	HSE Holding Slovenske elektrarne
Hungary	MVM Magyar Villamos Művek Zrt.	Spain	Iberdrola, SA
Ireland	ESB Electricity Supply Board	Sweden	Vattenfall
Italy	Enel SpA	United Kingdom	British Energy Group

Note: The time frame includes the years 2005–2016, except for the following companies: Enemalta (2005–2011; as of 2012, financial statements have not been available to the public), Essent Nederland B.V. (2005–2010; in 2010, RWE Power AG became the full owner of Essent), and PGE Polska Grupa Energetyczna SA (2007–2015; financial reports for 2005 and 2006 are not available to the public).

Table A2. Pearson correlation coefficients.

Variable.	Revenue	GHG	Asset	Employees	Investment
Revenue	1	-	-	-	-
GHG	0.8913 *	1	-	-	-
Asset	0.9529 *	0.7768 *	1	-	-
Employees	0.9059 *	0.8581 *	0.8380 *	1	-
Investment	0.5631 *	0.3664 *	0.5366 *	0.4831 *	1

Note: * statistically significant at the 0.05 significance level.

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