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Eco-efficiency assessment of the electricity sector: Evidence from 28 European Union countries

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ABSTRACT

This study is aimed at performing the eco-efficiency assessment of the electricity sector in 28 European Union countries. The novelty of our work resides in the combination of Data Envelopment Analysis with Input–Output analysis to perform the eco-efficiency evaluation of the consumption and production supply chains of the electricity sector. According to our findings, the only countries that increased their efficiency scores across all chains of the electricity sector were France (the only efficient country that increased its efficiency), Ireland (the only country that became efficient in all chains), the United Kingdom and Belgium. Additionally, the countries which were efficient across all chains, were France, Luxemburg, Germany, and Sweden while Poland, the Netherlands, Estonia (the only country in the top four lowest efficiency scores in all chains), Hungary, Croatia, Finland, Lithuania, Slovakia, the Czech Republic, Slovenia, and Greece remained inefficient. Overall, it can be concluded that the countries that fostered renewable energy deployment efficiently, gradually decommissioning fossil fuel generation, enhanced their potential in terms of eco-efficiency by reducing the emissions produced by the electricity sector and stimulating the growth of value-added created by it.

1. Introduction

The European Union (EU) brought to the policy agenda the promotion of economic growth, but specifically encompassing the reduction of greenhouse (GHG) emissions, making eco-efficiency a timely and relevant issue (Luptacik and Mahlberg, 2013).

The eco-efficiency concept is related to sustainability in the sense that it is a new indicator of economic performance but differs from this latter one in that it considers environmental and economic aspects leaving the social dimension unattended. Eco-efficiency is often defined as the ratio between the value-added and the impacts produced, aiming to increase the output of goods and services and decrease the resource inputs and emissions (Luptacik and Mahlberg, 2013). The evaluation of eco-efficiency is important to determine economic and environmental success, enabling the identification of trends, helping with the design of action plans and with the detection of areas for improvement. Eco-efficiency also differs from traditional technical efficiency in the way that this last concept is the ratio between desirable outputs and inputs, disregarding ecological aspects.

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Presently, there is an increasing research interest regarding the efficiency level of utility operations, along with the environmental impacts of the electricity production chain (Sueyoshi and Goto, 2018). Furthermore, since the electricity sector plays a prominent role in our society, it is important to develop approaches to appraise the level of sustainability of the technologies and energy mixes employed in electricity generation. There are a plethora of methods currently used for this purpose. Antunes and Henriques (2016) provided an overview of the application of multi-objective optimization and multi-criteria analysis models and methods in a vast range of energy problems, specifically addressing the electricity sector. Turconi et al. (2013) presented a comprehensive review of studies using life cycle assessment (LCA) for appraising the sustainability of electricity generation technologies. Vendries Algarin et al. (2015) suggested a methodological framework based on the Input–Output (IO) model for examining the economic, environmental, and policy implications of current and future power generation scenarios. Li et al. (2016) proposed a sustainability assessment index system to contrast the electricity generation system sustainability across G20 Countries.

Despite the distinctive features of the methodologies available to the same end, there is one common characteristic: they all cover a wide array of indicators involving the main sustainability dimensions (i.e. economic, environmental and social). Thus, one of the challenges involved in the assessment of the sustainability of the electricity sector is to combine into a single score the multiplicity of metrics available in a way that policy-making can be supported effectively (Zurano-Cervelló et al., 2019).

In this context, Charnes et al. (1978) paved the grounds for Data Envelopment Analysis (DEA), which is a non-parametric approach that allows assessing the relative efficiency of a set of decision-making units – DMUs (organizations under assessment) with homogeneous characteristics – according to several indicators either classified as inputs or outputs. With this methodology, DMUs are classified into efficient and inefficient according to an efficiency score.

Due to its flexibility, DEA provides help with the identification of possible sources of inefficiency offering public decision-makers the chance of studying ways to overcome them.

One of the main advantages of the application of DEA in efficiency assessment is the possibility of finding the benchmarks of inefficient DMUs, providing managers with valuable information regarding the best practices to be followed. These benchmarks are computed through linear programming (LP) models and are obtained just by using the original inputs and outputs.

Moreover, the DEA methodology has been broadly accepted and applied to assess the level of efficiency of the electricity sector (Sueyoshi and Goto, 2018) – see Table 1.

However, two major drawbacks subsist in the studies conducted so far using DEA models (see Table 1). Firstly, the scope of research has been mostly focused on the evaluation of the environmental impacts caused in the generation of electricity, taking mainly into account fuel consumption, setting aside other relevant impacts such as economic (e.g. impacts on Gross Domestic Product), also disregarding the separation of the production and consumption chains of the electricity sector. Secondly, except for the study conducted in Zurano-Cervelló et al. (2019), the data used in these studies are outdated (dating back to 2010).

This study aims at filling the main gaps identified in the literature, regarding the eco-efficiency assessment of the electricity sector, by proposing its empirical evaluation in 28 EU countries using Environmental Extended Input–Output (EEIO) tables in conjunction with DEA, considering the years of 2010 and 2014 (concerning the most updated data available). On the one hand, the use of EEIO tables allows broadening the scope of analysis enabling the incorporation of environmental impacts that are linked with a wide range of economic transactions between different activity sectors. On the other hand, the combination of IO analysis with DEA allows overcoming the limitations of previous studies using the IO approach which evaluated environmental and economic performances autonomously (Zurano-Cervelló et al., 2018) – a brief review of such studies is presented in Table 2.

This work has been inspired by a combination of studies in the field of eco-efficiency which were carried out by Lábaj et al. (2014) and Zurano-Cervelló et al. (2018). Lábaj et al. (2014) studied the economic growth in terms of welfare in 30 European countries using DEA models, while Zurano-Cervelló et al. (2018) merged the use of DEA models with IO tables to evaluate the eco-efficiency in the manufacturing sectors both considering production and consumption-based approaches.

The novelty of this work lies in the application of the DEA model through a Directional Distance Function (DDF) approach in combination with EEIO tables, also taking into account the production and consumption supply chains of the electricity sector. To the best of our knowledge, the application of this kind of approach to the electricity sector has never been developed before.

The outline of this paper is as follows: Section 2 describes the methodological approaches used in this study; Section 3 refers the main premises considered regarding data collection; Section 4 presents a discussion of some illustrative results; and, Section 5 provides some conclusions, suggesting future work developments.

2. Methodology and assumptions

In this section, some of the underpinning assumptions regarding the computation of the multipliers based on the EEIO tables are described. Then, the DEA DDF model will be briefly explained, as well as the underlying hypotheses for the choice of the inputs and outputs considered.

The different steps required to follow the methodological approach herein used are described below and are illustrated in Fig. 1.

Table 1
DEA models applied to the efficiency assessment of the electricity sector.

Reference	Description	Application	Inputs	Outputs	Models
Korhonen and Luptacik (2004)	Technical efficiency and Ecological efficiency analysis of power plants	24 power plants in the EU	Total costs of electricity generation	Electricity generation; Dust; NO_X and SO_2 emissions	CCR (Charnes et al., 1978)
Vaninsky (2008)	Environmental efficiency	Electricity power industry in the United States (1990–2006)	CO_2emissions; Electricity losses	Fossil fuel utilization	CCR; Environmental Index
Sueyoshi and Goto (2011)	Operational and environmental efficiency of energy firms	Fossil fuel power generation in Japan (2005-2008)	Generation capacity; $N^o$of Employees; Coal, oil and Liquid Natural Gas	Electricity Generation; CO_2 emissions	DEA non-radial measurement — Range-Adjusted Measure; Kruskal–Wallis rank sum test
Bai-Chen et al. (2012)	Efficiency assessment of generation and grid divisions	Power system in China (2002–2009)	Capital equipment; Fuel; Labour; Auxiliary power; On-grid electricity	Electricity generated; Electricity Consumed	CCR
Sueyoshi and Goto (2013)	Environmental assessment	Electricity sector in industrial nations from OECD (1999–2009)	Net electrical capacity of Fuel; Nuclear; Hydro; other renewables	Electricity generation; CO_2 emissions	Malmquist Index
Zhang and Kim (2014)	Energy eco-efficiency	Power companies in Korea (2007–2011)	Capital; Labour; Energy	Total turnover; GHG emissions	Slack-based measure (SBM);
Bi et al. (2014)	Relationship between fossil fuel consumption and environmental regulations	Thermal power generation in China (2007–2009)	Installed capacity; Labour; Total coal and gas	Power generated; SO_2 and NO_Xemissions; Soot.	SBM
Gómez-Calvet et al. (2014)	Energy Efficiency analysis	Electricity and derived heat in 25 EU countries (2000–2007)	Primary energy; Installed capacity; Labour	Electricity and Derived Heat; CO_2emissions; Radioactivity	DDF; SBM
Munisamy and Arabi (2015)	Eco-efficiency change	Thermal power plants (Steam, Gas and Combined Cycle) in Iran (2003–2010)	Installed capacity; Fuel consumption	Power generated; SO_2; NO_X and CO_X emissions; Operational availability; Deviation from Generation plan.	Meta-frontier Malmquist-Luenberger index; SBM
Galán-Martín et al. (2016)	Sustainability assessment	Electricity generation technologies expected to play a major role in a future UK electricity mix.	Capital cost; Operation and maintenance cost, Fuel cost; Freshwater eco-toxicity; Marine eco-toxicity; Global warming; Ozone depletion; Acidification; Eutrophication; Photochemical smog; Land occupation and eco-toxicity; Direct employment; Worker injuries; Human toxicity potential; Radiation; Depletion of elements; Depletion of fossil fuels	Production of 1 kWh of electricity	Enhanced DEA
Ewertowska et al. (2016).	Environmental performance	Electricity mix of the top 27 European economies.	Acidification; Climate change; Eutrophication; Aquatic eco-toxicity; Sediment eco-toxicity; Human toxicity; Ionizing radiation; Land use; Malodorous air; Photochemical oxidation; Resources antimony; Stratospheric ozone; Terrestrial eco-toxicity	Production of 1 kWh of electricity	LCA; CCR
Halkos and Polemis (2018)	Environmental efficiency	Electricity sector in the United States (2001, 2002 and 2003)	Total energy transmission; Total operation costs	Utilization of net capacity; CO_2; SO_2 and NO_Xemissions	Window DEA; Hybrid model Parametric and non-parametric econometric technique
Zurano-Cervelló et al. (2019)	Sustainability efficiency assessment of the power sector	Electricity mix of 28 EU members(2015)	Fossil fuel depletion; Total land occupation, Water depletion; Annualized cost of electricity; Climate change; Human toxicity and Ozone depletion; Total jobs per year	Electricity generated	LCA; BCC; Mathematical programming tools

The first step consisted in establishing the adjusted EEIO methodological framework for each country for 2010 and 2014, by combining the use of National IO tables with Social Accounting and Air Emissions Accounting tables. In the second step, the DEA model has been employed to evaluate the eco-efficiency of each decision-making unit (DMU) under assessment, which in this study corresponds to each country.

2.1. The IO multipliers

The IO model uses a table which depicts the economic transactions among industries that can encompass other sorts of information, by adding new columns and rows that correspond to the energy used or to the pollutants emitted per each industrial sector, i.e. the EEIO tables (Hendrickson et al., 2006).

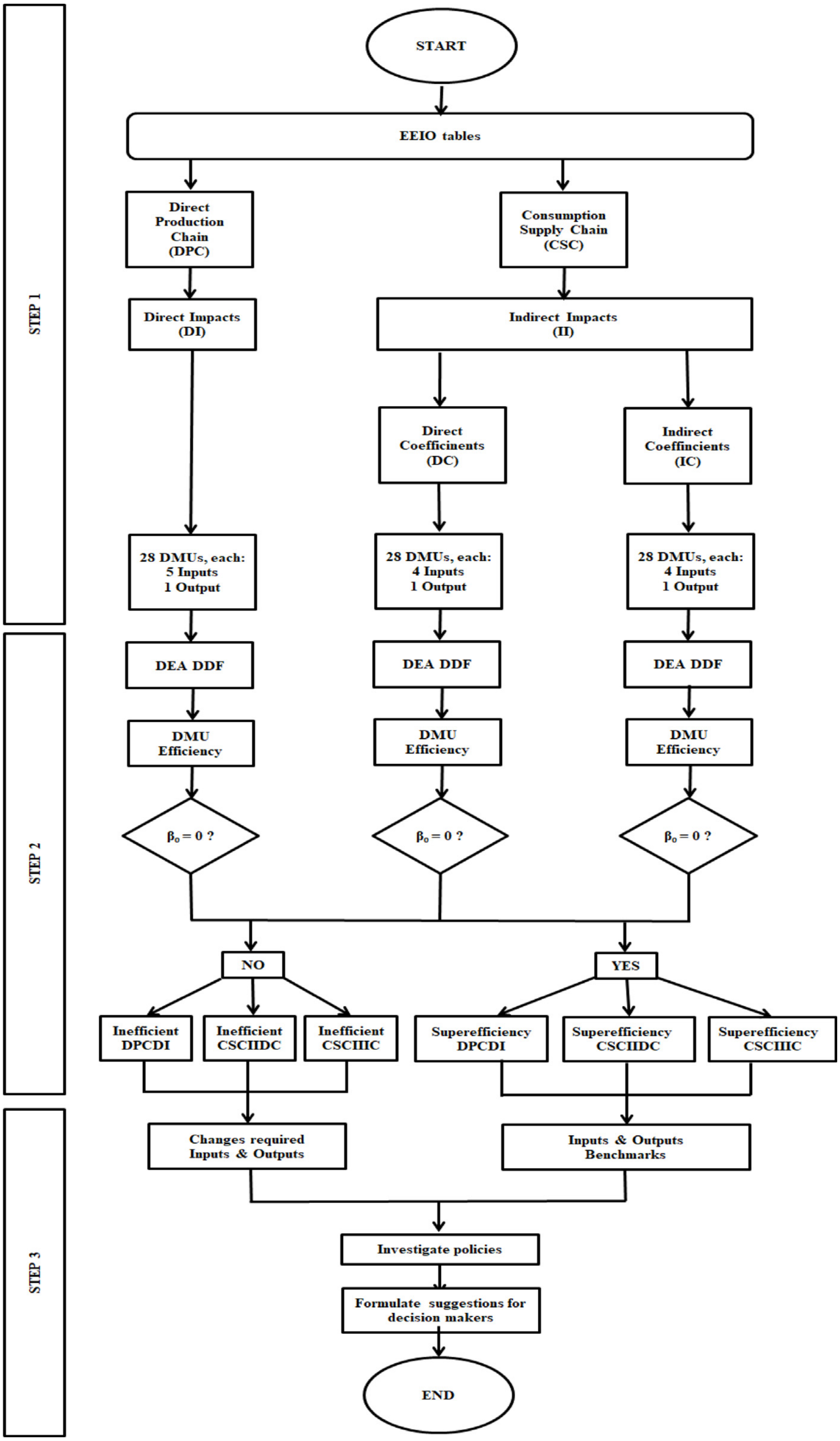

Fig. 1. Diagrammatic illustration of the methodological framework used.

Table 2
Studies with the application of IO to electricity generation.

IO focus	Years covered	Electricity sector disaggregation	Methodologies	Reference
Net employment of renewable electricity generation (RES-E) in the Federal Republic of Germany	1999–2017	Not specified	Symmetric IO framework	Ziegelmann et al. (2000)
CO_2 emissions affected by the substitution of the conventional coal technology with cleaner technologies in Thailand	2006–2016	Electricity from coal, lignite, natural gas, fuel oil, diesel oil and biomass, hydro and other renewable electricity	Symmetric IO framework	Limmeechokchai and Suksuntornsiri (2007)
Economic consequences and CO_2emissions of changes in Scotland's electricity generating capacity and mix	2000	Electricity distribution transmission and supply for eight technologies	Symmetric IO framework	Allan et al. (2007)
Pollution emission from electric power industries in the Malaysian economy	1991–2000	Fuel, hydroelectricity and other	Symmetric IO framework	Al-Amin et al. (2009)
Employment benefits of RES-E in Greece	2020	Wind, Photovoltaic Power (PV), Hydro, Geothermal and Biomass	Symmetric IO framework	Tourkolias and Mirasgedis (2011)
CO_2 emissions for conventional and RES-E for several regions in the USA.	2002	Generation (Conventional and RES-E), transmission and distribution	Supply and use tables (SUT) framework	Vendries Algarin et al. (2015)
Macroeconomic effects associated with several energy conservation measures in Greece	2010–2020	Electricity sector is not disaggregated	Symmetric IO framework	Markaki et al. (2013)
Socio-economic impacts of geothermal power generation in the Japanese economy	Geothermal power plant life cycle (30 years).	Five sectors related to geothermal power generation	Symmetric IO framework	Hienuki et al. (2015)
Environment, Energy and economic impact of a wind power generation system in Japan	Wind power plant life cycle.	Sectors related to wind turbine manufacturing and construction and "Wind power utility"	SUT framework	Nagashima et al. (2016)
Employment impacts of electricity sector in Portugal	2008–2020	Wind, PV, Hydro, Geothermal, Biomass, Coal and Natural Gas	Symmetric IO framework (quantity and price models)	Henriques et al. (2016)
Economic Impacts of Wind and Solar Photovoltaic Power Development in China	2016–2030	Wind and Solar PV	SUT framework	Li et al. (2017)

Direct effects evaluate the impacts on a given industry as a result of the variation in the final demand of that same industry. Indirect effects assess the reaction of the supply chain of that industry from an increase (decrease) in its final demand. The overall effect adds together direct and indirect effects.

According to IO analysis the total output of each activity sector is distributed for intermediate consumption and/or final demand. Eq. (1) depicts the delivery of the total output of each activity sector:

$$x_i = \sum_{j=1}^{n} x_{ij} + \sum_{f=1}^{m} y_{if} \tag{1}$$

where x_i is the output of sector i, x_{ij} is the delivery of input from sector i to sector j, and y_{if} is the delivery of input of sector i to the final demand sector f.

Assuming the hypothesis of constant returns to scale, Eq. (1) becomes:

$$x_i = \sum_{j=1}^{n} a_{ij} x_j + \sum_{f=1}^{m} y_{if} \tag{2}$$

in which a_{ij} are the coefficients that reflect the amount of inputs from sector i distributed to sector j per unit of output of this latter activity sector. These coefficients are also called technological coefficients (or direct coefficients).

In its matrix form, the national productive system can be given as (Miller and Blair, 2009):

$$\mathbf{x} = A\mathbf{x} + \mathbf{y}, \tag{3}$$

where A is the technological coefficients matrix, **y** is the final demand vector (households, government, firms, and foreign countries) and **x** is the output vector.

The energy consumed and pollutant emissions created by inter-industrial activities are obtained through the use of a direct coefficients matrix, E, where each component, e_{kj}, corresponds to the quantity of energy (pollutants) of type k spent (emitted) per output unit of each industry j (Hendrickson et al., 2006). Therefore, the level of energy use (the level of pollutant emissions) intertwined with a certain output vector is:

$$\mathbf{e} = E\mathbf{x}, \tag{4}$$

where **e** is the vector of each type of energy (pollutant) directly and indirectly consumed (emitted) by the economy in supplying a certain final demand level.

From (3) and (4), E (I – A)$^{-1}$ can be regarded as the matrix of total energy usage coefficients, such that:

$$\mathbf{e} = E(I - A)^{-1}\mathbf{y}. \tag{5}$$

Each component of this matrix provides the energy used (pollutants emitted) per monetary unit of final demand.

2.2. The DDF approach

In general, DEA models can be grouped into four classes (Cooper et al., 2006): (1) radial and oriented, (2) radial and non-oriented, (3) non-radial and oriented, and (4) non-radial and non-oriented. In this context, by 'radial' it is meant the required proportional increase or reduction of outputs/inputs to reach efficiency, whereas 'oriented' refers to input-oriented or output-oriented DEA problems. Hence, we have used the DDF model, which is a radial and non-oriented model, since unlike the input (output)-oriented models it can provide a more comprehensive efficiency assessment.

Given two vectors of inputs and outputs, $\boldsymbol{x} = (x_1, \ldots, x_n)^T$ and $\boldsymbol{y} = (y_1, \ldots, y_n)^T$, respectively, the DEA piecewise reference technology can be obtained as follows:

$$\begin{aligned} T = \{(\boldsymbol{x}, \boldsymbol{y}) : &\sum_{j=1}^{n} \lambda_j y_{rj} \geq y_r, r = 1, \ldots, s, \\ &\sum_{j=1}^{n} \lambda_j x_{ij} \leq x_i, i = 1, \ldots, m, \\ &\lambda_j \geq 0, j = 1, \ldots, n\}, \end{aligned} \tag{6}$$

In what regards the reference technology T considered in (6), traditionally, for each DMU under assessment, DMU$_o$, the DDF can be obtained by solving the following LP problem:

$$\begin{aligned} &\max \beta_o \\ &\text{s.t.} \sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{ro} + \beta_o g_{yr},\ \ r = 1, \ldots, s, \\ &\sum_{j=1}^{n} \lambda_j x_{ij} \leq x_{io} - \beta_o g_{xi},\ \ i = 1, \ldots, m, \\ &\lambda_j \geq 0\ (\forall_j) \end{aligned} \tag{7}$$

where β_o measures simultaneously the maximum enlargement of outputs and reduction of inputs that remain technically feasible and can serve as a measure of technical inefficiency. If $\beta_o = 0$, then DMU$_o$ operates on the frontier of T with technical efficiency. If $\beta^o > 0$, then DMU$_o$ operates inside the frontier of T and it is inefficient. Finally, the parameter $\beta_o g_{xi}$ indicates the level by which DMU$_o$ has to reduce its i-th input to become efficient. Analogously, the parameter $\beta_o g_{yr}$ provides information on the level by which DMU$_o$ has to enlarge its r-th output to become efficient.

In order to account for variable returns to scale it is only necessary to add the constraint $\sum_{j=1}^{n} \lambda_j = 1$ into model (7).

Besides being a generalization of the Shephard's distance functions, the DDF can be specified to embed different assumptions (Färe and Grosskopf, 2010). We have considered $\boldsymbol{g} = (-\boldsymbol{g}_x, \boldsymbol{g}_y)$= $(-\boldsymbol{x}^o, \boldsymbol{y}^o)$, i.e., the direction is set to account for the observed data and β^o corresponds to the potential proportional variation in outputs and inputs.

The DDF model can also be used for the definition of superefficiency. The super-DDF model considers that the efficiency scores of the inefficient DMUs are kept unaffected and the efficiency scores of the efficient DMUs are bigger than 1, thus allowing for the classification of efficient DMUs. This type of approach was first suggested in the model proposed by

Andersen and Petersen (1993). In order to obtain the super-DDF model it is necessary to remove the efficient DMU$_o$ under evaluation form the set of DMUs. In order to rank the efficient DMUs the following problem should be solved:

$$\begin{aligned}
&\max \beta_o\\
&\text{s.t.} \sum_{j\neq o}^{n} \lambda_j y_{rj} \geq y_{ro} + \beta_o g_{yr},\ \ r = 1, \ldots, s,\\
&\sum_{j\neq o}^{n} \lambda_j x_{ij} \leq x_{io} - \beta_o g_{xi},\ \ i = 1, \ldots, m,\\
&\sum_{j\neq o}^{n} \lambda_j = 1, \lambda_j \geq 0\ (\forall_j),
\end{aligned} \tag{8}$$

Halkos and Petrou (2019) provide a comprehensive review of the available approaches to handle undesirable outputs in DEA models. They classify these approaches into direct and indirect ones. The direct approaches handle undesirable inputs/outputs in their original form, i.e. using parametric output and input distance functions and DEA methods.

The indirect approaches treat the undesirable outputs as classical inputs. With this regard, we will follow the indirect approach.

Therefore, the following problem is obtained:

$$\begin{aligned}
&\max \beta_o\\
&\text{s.t.} \sum_{j=1}^{n} \lambda_j y_{rj}^{g} \geq y_{ro}^{g} + \beta_o g_{yr}^{g},\ \ r\epsilon GO,\\
&\sum_{j=1}^{n} \lambda_j y_{rj}^{b} \leq y_{ro}^{b} - \beta_o g_{yr}^{b},\ \ r\epsilon BO,\\
&\sum_{j=1}^{n} \lambda_j x_{ij}^{g} \leq x_{io}^{g} - \beta_o g_{xi}^{g},\ \ i\epsilon GI\\
&\sum_{j=1}^{n} \lambda_j = 1, \lambda_j \geq 0\ (\forall_j),
\end{aligned} \tag{9}$$

where all *GO*/*GI* and *BO* are the indexes that designate the presence of good outputs/inputs and bad outputs, respectively; the vectors of desirable inputs and outputs (g) of DMU$_o$ are given as $\boldsymbol{x}_o^g$ and $\boldsymbol{y}_o^g$, correspondingly, while the vectors of undesirable outputs (b) of DMU$_o$ are given as $\boldsymbol{y}_o^b$, respectively, and all variables are nonnegative except for β_o.

One of the main advantages of the application of DEA in efficiency assessment is the possibility of finding the benchmarks of inefficient DMUs, providing valuable information for managers regarding best practices. The benchmarks of an inefficient DMU are computed through linear programming (LP) models. The reference set of the inefficient DMU$_o$ based on (9) is obtained by solving the following LP problem, considering that β_o^*, is obtained in the optimal solution to (9):

$$\begin{aligned}
&\max \sum_{r\epsilon CGO} s_r^+ + \sum_{r\epsilon CBO} s_r^- + \sum_{i\epsilon CGI} s_i^-,\\
&\text{s.t.} \sum_{j=1}^{n} \lambda_j y_{rj}^{g} - s_r^+ = y_{ro}^{g} + \beta_o^* g_{yr}^{g},\ \ r\epsilon GO,\\
&\sum_{j=1}^{n} \lambda_j y_{rj}^{b} + s_r^- = y_{ro}^{b} - \beta_o^* g_{yr}^{b},\ \ r\epsilon BO,\\
&\sum_{j=1}^{n} \lambda_j x_{ij}^{g} + s_i^- = x_{io}^{g} - \beta_o^* g_{xi}^{g},\ \ r\epsilon GI,\\
&\sum_{j=1}^{n} \lambda_j = 1,\ \ \lambda_j \geq 0(\forall_j),
\end{aligned}$$

Table 3
A review of studies which combine DEA with IO analysis.

Reference	Application	Inputs	Outputs	Models used
Luptacik and Bohm (2006)	Eco-efficiency in an IO model	Labour; Capital	Pollutant Abatement activities	Augmented IO model; CCR; BCC (Banker, 1984); SBM
Luptacik and Mahlberg (2013)	Eco-efficiency and eco-productivity change over time in an IO model Austria (1995–2007)	Labour; Capital	Final demand; Air emissions	Augmented Leontief IO model; CCR Malmquist-Luenberger index
Lábaj et al. (2014)	Eco-efficiency and socio-economic efficiency in terms of welfare 30 European countries (2010)	Labour; Capital	Gross Domestic Product (GDP); Emissions	BCC
Zurano-Cervelló et al. (2018)	Eco-efficiency assessment of EU manufacturing sectors 27 EU countries (2009)	Global warming potential (GWP); Potential Acidifying equivalent (PAE); Tropospheric ozone forming potential TOFP)	Total economic output	Multi Regional EEIO tables; CCR; Super-efficiency

$$s_r^+ \geq 0(\forall_{r\epsilon GO}),\ \ s_r^- \geq 0\ (\forall_{r\epsilon BO}),$$

$$s_i^- \geq 0\ (\forall_{i\epsilon GI}), \tag{10}$$

Let $(\beta_o^*, s_r^{+*}, s_r^{-*}, s_i^{-*}, \lambda_j^*)$ be the optimal solution to (10). Consider the reference set of the DDF-inefficient DMU$_o$ as follows:

$$E_o = \{j : \lambda_j^* > 0, j = 1, \ldots, n\}. \tag{11}$$

The point of the efficient frontier which can be viewed as a target DMU for the DDF-inefficient DMU$_o$ is given by:

$$(\hat{\boldsymbol{x}}_o, \hat{\boldsymbol{y}}_o) = (\sum_{j\epsilon E_0} \lambda_j^* \boldsymbol{x}_j^g, \sum_{j\epsilon E_0} \lambda_j^* \boldsymbol{y}_j^g, \sum_{j\epsilon E_0} \lambda_j^* \boldsymbol{y}_j^b). \tag{12}$$

Definition 1. Let β_o^* be the optimal solution of model (9). Let s_r^{+*}, $r\ \epsilon GO$, s_r^{-*}, $r\ \epsilon BO$, s_i^{-*}, $i\ \epsilon GI$, be the optimal solutions to model (10). The DMU$_o$ is considered:

(1) Strong efficient for the non-oriented DDF model, if and only if β_o^* = 0 and $\sum_{r\epsilon GO} s_r^{+*} + \sum_{r\epsilon BO} s_r^{-*} + \sum_{i\epsilon GI} s_i^{-*} = 0$.

(2) Weak efficient for the non-oriented DDF model, if and only if β_o^* = 0 and $\sum_{r\epsilon GO} s_r^{+*} + \sum_{r\epsilon BO} s_r^{-*} + \sum_{i\epsilon GI} s_i^{-*} \neq 0$.

(3) Inefficient for the non-oriented DDF model, if and only if $\beta_o^* \neq 0$.

2.3. The selection of inputs and outputs

One of the greatest challenges in a DEA model formulation is the identification of the truly significant input and output variables. Although the available literature on the selection of these factors is not prolific, several approaches can be used to deal with this particular problem (Nataraja and Johnson, 2011).

In our case, since we wanted to combine IO analysis with DEA, we have started the selection procedure by considering the contributions of previous studies by Luptacik and Bohm (2006), Luptacik and Mahlberg (2013), Lábaj et al. (2014) and Zurano-Cervelló et al. (2018) (see Table 3).

From these studies it was possible to draw some conclusions about the approaches taken, the countries selected, as well as the inputs and outputs chosen. Regarding the methodologies used, it was possible to conclude that the DEA models usually employed did satisfy our requirement of using a radial model but did not use a non-oriented approach. Therefore, we have selected the radial non-oriented DDF model. The choice of the 28 EU countries originated from linking Lábaj et al. (2014) and Zurano-Cervelló et al. (2018) studies, where the former assessed the efficiency of EU27, while the latter assessed the eco-efficiency of 30 European countries. Finally, these two studies were also responsible for the choice of the inputs and outputs presented in Table 4.

Table 4
Input and output factors.

Inputs	Definition	Units
1 – Labour	Number of jobs in full time equivalent (FTE)	1000 employees
2 – Capital stock	Nominal Capital Stock (K)	10^6 €
3 – GHG emissions	GHG emissions	1000-ton CO_2 eq.
4 – ACG emissions	Acidifying gas (ACG) emissions	1000-ton SO_2 eq.
5 – O3PR	Ozone precursors (O3PR)	1000-ton NMVOC eq.
Outputs	**Definition**	**Units**
GVA	Gross Value-added (GVA) - Monetary value for the amount of goods and services that have been produced, less the cost of all inputs and raw materials that are directly attributable to that production.	10^6 €

Note: CO_2– carbon dioxide; SO_2– sulphur dioxide; NMVOC — Non-methane volatile organic compounds; €- euro, eq. - equivalent.

Table 5
Descriptive statistics of all DMUs — direct production chain.
Source: Authors' own calculations.

		Labour (X1000)	*K (x10^6 €)*	*GHG (x1000 ton)*	*ACG (x1000 ton)*	*O3PR (x1000 ton)*	*GVA (x10^6 €)*
2010	Minimum	1	404	1,206	1	3	70
	Maximum	249	219,861	357,283	652	423	56,033
	Average	47	39,002	47,401	122	82	8,108
	Standard deviation	61	54,220	75,520	166	115	12,214
2014	Minimum	1	550	765	1	2	43
	Maximum	250	222,906	352,117	497	407	49,571
	Average	45	44,493	41,284	87	68	8,432
	Standard deviation	60	58,483	72,323	129	104	12,222

3. Data and assumptions

The application of the IO approach in the framework of electricity generation can be a complex and challenging task since published IO tables only allow assessing the impact of an increase in demand for electricity in general (Henriques et al., 2016). Published IO tables consider a single aggregated electricity, gas, steam and air conditioning supply sector; where generation, transmission, distribution and supply activities related to the production and use of electricity are included. Since in the years considered for this study the weight of the electricity sector on the value-added and employment levels of this aggregate activity sector accounted in average for more than 75%, this sector will be used as a proxy of the electricity sector (Eurostat, 2015).

Data on non-environmental inputs and outputs directly used in the direct production chain of the European Union Electricity sector were obtained from the Social Accounts Released in 2016, published in February 2018 by the World IO database (Timmer et al., 2015) – Figures 1S to 3S (supplementary material). Environmental bad outputs, treated as inputs (i.e. GHG emissions, acidifying gas substances and ozone precursors) were obtained from the Air Emission Accounts – OECD estimates (OECD, 2018) – Figures 4S to 6S (supplementary material). Table 5 provides information on the descriptive statistics regarding the inputs and outputs considered in 2010 and 2014, respectively.

Table 5 allows us to conclude that there was a decrease in the average environmental emissions from 2010 to 2014 in the direct production chain of the electricity sector, although the average capital stock and GVA were higher. These results are consistent with the increase of renewable generation (31%) and the decrease of fossil fuel generation (20%) in the EU28, during this time frame (European Commission, 2018).

Data on non-environmental inputs and outputs used in the consumption supply chain (both considering the sectors, directly and indirectly, engaged with the Electricity sector) were obtained from the IO multipliers computed through the IO tables published by the World IO database (Timmer et al., 2015) – Figures 7S to 10S (supplementary material). In the case of environmental bad outputs, which were treated as inputs (i.e. GHG emissions, acidifying gas substances and ozone precursors) the multipliers were computed through the IO tables published by the World IO database and the Air Emission Accounts – OECD estimates (OECD 2018) – Figures 11S to 16S (supplementary material). Tables 6 and 7 provide information on the descriptive statistics regarding the inputs and outputs considered in the direct and indirect consumption supply chains of the electricity sector in 2010 and 2014, respectively. Finally, it is worth mentioning that capital stock is no longer considered as an input in the consumption supply chain to avoid double-counting since this sector is already incorporated in final demand.

From the analysis of Tables 6 and 7 it might be established that the activity sectors included in the direct consumption supply chain of the electricity sector have a lower value for inputs and outputs than the sectors in the indirect consumption supply chain, mainly due to the contribution of sector D35 — Electricity, gas, steam and air conditioning supply. This

Table 6
Descriptive statistics of all DMUs — direct consumption supply chain.
Source: Authors' own calculations.

		Labour (X1000)	*GHG (x1000 ton)*	*ACG (x1000 ton)*	*O3PR (x1000 ton)*	*GVA (x10^6 €)*
2010	Minimum	0	110	0	0	18
	Maximum	150	23,958	47	60	11,077
	Average	20	3,344	8	7	1,489
	Standard deviation	30	5,914	11	13	2,463
2014	Minimum	0	5	0	0	16
	Maximum	148	21,975	37	54	11,285
	Average	19	2,861	6	6	1,598
	Standard deviation	30	5,121	9	11	2,681

Table 7
Descriptive statistics of all DMUs — indirect consumption supply chain.
Source: Authors' own calculations.

		Labour (x1000)	*GHG (x1000 ton)*	*ACG (x1000 ton)*	*O3PR (x1000 ton)*	*GVA (x10^6 €)*
2010	Minimum	1	439	1	1	36
	Maximum	215	144,848	232	176	29,249
	Average	36	18,334	47	33	4,032
	Standard deviation	48	29,660	63	47	6,208
2014	Minimum	1	338	0	1	26
	Maximum	213	152,050	185	179	27,997
	Average	35	16,418	34	28	4,291
	Standard deviation	48	30,136	50	43	6,535

sector presents a level of emissions and a GVA superior to the remaining sectors of both chains combined since all sectors directly engaged to the electricity sector are dependent on the electricity sector itself for their economic activity. In the direct consumption supply chain, the average environmental emissions decreased as well as labour, while GVA had a slight increase from 2010 to 2014. The top five sectors contributing to the electricity sector emissions, both in 2010 and 2014, were: the electricity sector (D35 — Electricity, gas, steam and air conditioning supply.[1]), B - Mining and quarrying, H49 — Land transport and transport via pipelines, C19 — Manufacture of coke and refined petroleum products and E37–E39 — Sewerage; waste collection, treatment, and disposal activities; materials recovery; remediation activities and other waste management services. If we isolate ACG or O3PR emissions, sectors E37–E39 are replaced by sector A01 — Crop and animal production, hunting and related service activities in the top five contributors.

Finally, the indirect consumption supply chain follows a similar trend. In this latter case, the top five sectors contributing to electricity sector emissions, both in 2010 and 2014, were the same obtained in the direct consumption supply chain, exception made for C19 which is replaced by C23 — Manufacture of other non-metallic mineral products. If we specifically address ACG or O3PR emissions, sectors E37–E39 and C23 are replaced by A01, and H50 — Water transport.

4. Discussion of some illustrative results

4.1. Production chain

The study involved applying models (8) to (10) to the 28 DMUs under evaluation. Tables 1S to 6S (supplementary material) depict the overall efficiency scores ($1 - \beta_o$) (obtained with the super-efficiency model) for the periods of 2010 and 2014. Tables 7S to 10S (supplementary material) present information on the descriptive statistics of both efficient and non-efficient DMUs. From the analysis of these tables, it might be concluded that the average superefficiency values of efficient DMUs have slightly decreased from 2010 to 2014, mainly due to a mild reduction of the environmental impacts at the expense of a reduction of the GVA and an increase of the stock of capital. In what concerns the inefficient DMUs, the average inefficiency score follows a similar downward trend, but with a slight increase of the GVA at expense of a larger percentage increase of the stock of capital.

The growth of the stock of capital is consistent with the data referring to the same period in EU28 that shows an increase of 40% of the installed capacity of renewable electricity, whereas the installed capacity of fossil fuels and nuclear power declined 1% and 6%, respectively. Wind power and Solar Photovoltaic (PV) were the renewable electricity sources that faced a higher increase, ending the year of 2014 with 129GW and 87GW, respectively (European Commission, 2018).

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[1] The identification of all sectors of the consumption supply chain, mentioned as responsible for the changes of inputs and output of the electricity sector throughout this work, is presented in Table A.1 (Appendix A)

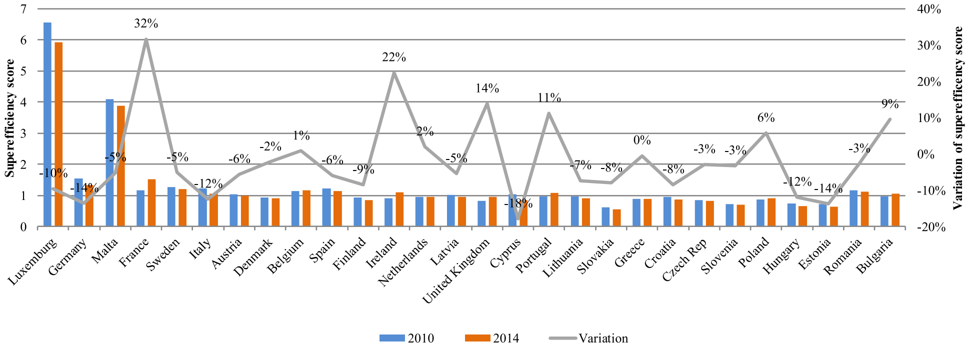

Fig. 2. Superefficiency scores in 2010 and 2014 — Direct Production Chain.

In 2010, Table 1S (supplementary material) shows the existence of 12 efficient countries (Luxemburg, Malta, Germany, Sweden, Spain, Italy, Romania, France, Belgium, Austria, Cyprus, and Latvia) from which the three countries more often selected as benchmarks regarding the direct production chain of the electricity sector were Malta, Germany, and Belgium (these last two *ex aequo*). In 2014, there are also 12 efficient countries (Luxemburg, Malta, France, Germany, Sweden, Belgium, Spain, Romania, Ireland, Portugal, Italy, and Bulgaria) from which the top four countries mainly considered as benchmarks were Ireland and France followed by Malta and Luxemburg (these last two *ex aequo*) –Table 2S.

The countries with the lowest eco-efficiency performance both in 2010 and in 2014 were Hungary, Estonia, Slovenia, and Slovakia — Tables 1S and 2S (supplementary material).

In 2014, Austria, Cyprus, and Latvia lost their efficiency status while Ireland, Portugal and Bulgaria became efficient – Fig. 2.

After analysing the superefficiency scores attained (Fig. 2), we can establish some important facts. When considering the period as a whole, we can point out that except for the countries that have become efficient, only Poland, the Netherlands, and the United Kingdom, which remained inefficient, and France and Belgium, which continued efficient, have increased their efficiency scores.

In this case, although the superefficiency scores obtained provide us an overall outcome for the economic and environmental efficiency of the joint use of production factors, such as capital and labour, it is important to know what factors influence the eco-efficiency performance of these countries.

Additionally, since the type of efficiency under analysis is not only economic but also environmental, i.e., we are considering environmental pollutant emissions from electricity generation, the source of energy used (fossil fuels, nuclear or renewable energy) is also relevant to the eco-efficiency performance outcomes. Therefore, it is expected that countries that invested in renewable energy deployment efficiently, progressively replacing fossil fuel generation, will have a higher potential in terms of eco-efficiency.

For example, in the case of Portugal (which expanded GVA and capital stock by 2% and 6%, respectively, and labour dropped by 11%), Ireland (which increased GVA and capital stock by 46% and 13%, respectively, and labour decreased by 17%) and Bulgaria (which boosted GVA and capital stock by 22% and 16%, respectively, and labour declined by 16%), which become efficient in 2014, the enhancement of eco-efficiency performance seems to be the result of improving the average productivity of capital and labour, with a reduction in fossil fuel generation and the increased production of renewable energy (according to the European Commission (2018) Portugal, Ireland and Bulgaria increased their renewable generation by 13%, 72%, and 24% and reduced their fossil fuel generation by 20%, 21%, and 5%, respectively) – Fig. 3.

Regarding France, a similar conclusion is reached, despite the 5% increase of labour, since there has been an increase of the GVA and capital stock of 29% and 20%, respectively, while electricity generation from renewables has increased by 18% and fossil fuel electricity generation dropped 51% (European Commission, 2018). The improvement of the efficiency of Belgium is mainly explained by the 70% renewable electricity generation increase and a 37% fuel generation decrease (European Commission, 2018), at the expense of an increase in capital by 14%, maintaining the same level of labour, with a substantial reduction of the overall emissions (28% for GHG, 42% for ACG and 37% for O3PR emissions) with a mild reduction of GVA (3%).

In what concerns the countries with lower eco-efficiency performance in 2014, the factors that seem to be sustaining this outcome, according to the projections of the DDF model, are the need to increase the average productivity of labour (Austria, Latvia, Lithuania, Croatia, Hungary, Estonia, Slovenia, and Slovakia) and capital (Denmark, Hungary, Estonia, Slovenia, and Slovakia), whereas GHG emissions can also become a critical factor in terms of eco-efficiency (Czech Republic, Slovakia, Estonia, Greece, Hungary, Cyprus, and Slovenia). This is particularly evident in the case of Netherlands due to an increase of electricity generation from solid fuels and petroleum products (31% and 52%; respectively) leading to a required reduction of 76% of GHG emissions, while the remaining non-efficient countries seem to require an improvement of their current environmental performance, that goes beyond their deployment on renewable energy.

These results have a similar trend across ACG and O3PR emissions as well.

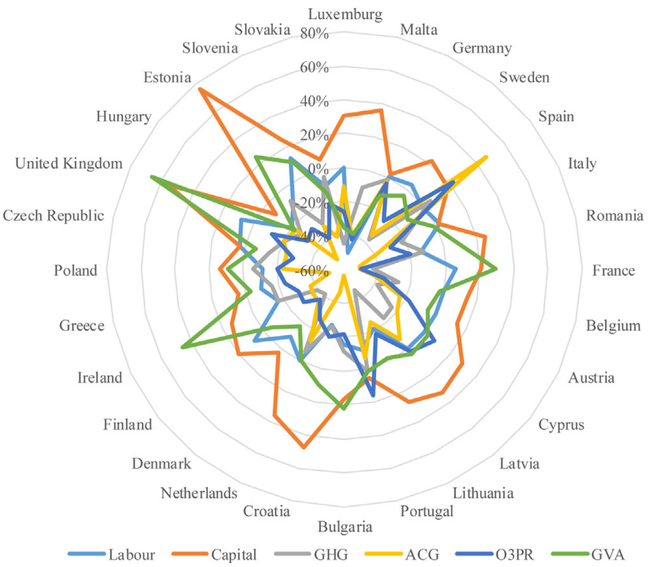

Fig. 3. Changes of inputs and outputs between 2010 and 2014 — Direct Production Chain.

Finally, the GVA is particularly relevant for enhancing eco-efficiency for Slovakia, Estonia, Hungary, and Slovenia. The overall adjustments prescribed by the DDF model regarding the direct production chain of the electricity sector are provided in Figures 17S to 22S (supplementary material).

4.2. *Direct consumption supply chain*

Tables 11S to 14S (supplementary material) present information on the descriptive statistics of both efficient and non-efficient DMUs in the case of the eco-efficiency assessment of the direct consumption supply chain of the electricity sector.

From the examination of these tables, it might be concluded that the average superefficiency values have increased from 2010 to 2014, mainly due to Cyprus, although labour and environmental impacts experienced a significant reduction at the expense of a slight reduction of its GVA. In what concerns the inefficient DMUs, the average inefficiency score suffered a decrease due to an increase of GVA and as a result of increasing emissions and decreasing labour productivity.

In 2010, Table 3S (supplementary material) shows the existence of 9 efficient countries (Cyprus, Luxemburg, Germany, Denmark, Sweden, Belgium, France, the United Kingdom, and Italy) from which the three countries more often selected as benchmarks (regarding the direct consumption supply chain of the electricity sector) were Luxembourg, Denmark, and Sweden (these last two *ex aequo*). In 2014, Table 4S (supplementary material) shows 10 efficient countries (Cyprus, Luxemburg, Germany, Denmark, Sweden, Belgium, France, the United Kingdom, Malta, and Ireland) from which the top three countries mainly viewed as a reference in terms of best practices were Denmark followed by Cyprus and Sweden (these last two *ex aequo*).

The countries with the lowest eco-efficiency performance both in 2010 and in 2014 were Bulgaria, the Czech Republic and Romania — Tables 3S and 4S (supplementary material).

In 2014, Italy lost its efficiency status while Ireland and Malta became efficient – Fig. 4.

From the super efficiency scores attained (Fig. 4), we can conclude that excluding the countries that have become efficient, only Croatia, Estonia, Finland, Greece and Lithuania, which remained inefficient, and Belgium, Cyprus, France, and the United Kingdom, which stayed efficient, have increased their efficiency scores.

In the case of the direct consumption supply chain, the consumption of the sectors directly linked to the electricity sector helps explain the evolution of the efficiency scores presented in Tables 3S and 4S (supplementary material). In fact, the electricity sector is the main responsible for the emissions in the direct consumption supply chain, because of intra-sector trade relations.

Regarding the countries that became efficient, Ireland increased its economic and labour productivity and decreased ACG and O3PR emissions although the GHG emissions have increased 6%, as a result of increasing the emissions in sector D35.

Regarding the other countries that increased their efficiency, they can be divided into two sets: the group of efficient and the group of inefficient.

In the first group, Belgium, France, and the United Kingdom decreased significantly their emissions and increased slightly their GVA while Cyprus had a singular behaviour characterized by decreasing substantially its environmental impacts and strongly its GVA – Fig. 5.

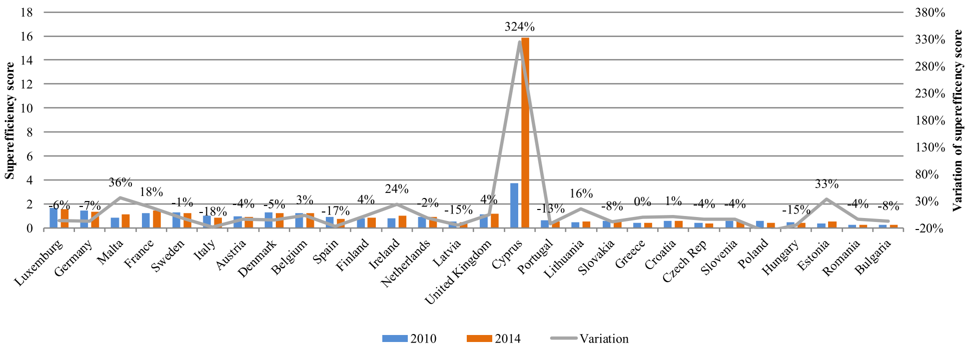

Fig. 4. Super efficiency scores in 2010 and 2014 — Direct consumption supply chain.

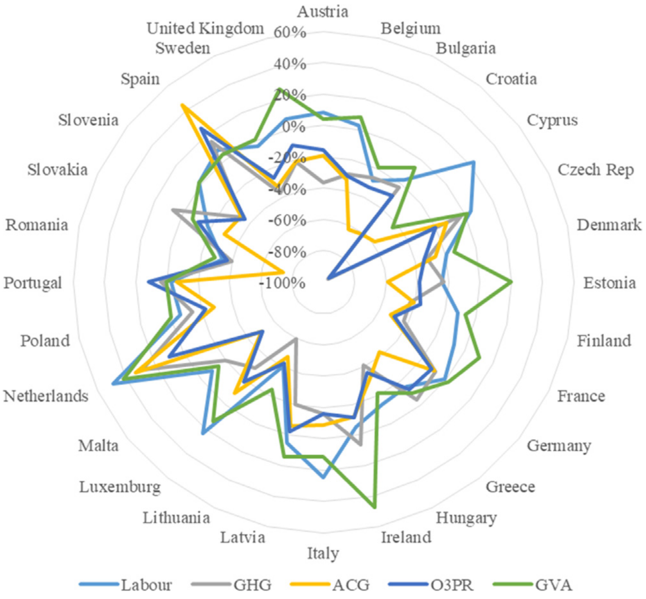

Fig. 5. Changes of inputs and outputs between 2010 and 2014 — Direct consumption supply chain.

The second group of countries, such as Croatia, Estonia Finland, Greece, and Lithuania experienced a strong reduction in GHG, ACG and O3PR emissions as well as on labour. Moreover, Estonia, Finland, Greece, and Lithuania have the same sector (D35) responsible for their environmental behaviour, facing a strong emission reduction from 2010 to 2014.

In what concerns the countries with lower eco-efficiency performance in 2014, the factors that seem to be sustaining this outcome, according to the projections of the DDF model, are the need to increase the average productivity of labour (Romania, Bulgaria, Czech Republic, Hungary, and Poland), the environmental performance by reducing GHG emissions (Greece, Estonia, Bulgaria, Czech Republic, and Romania), reducing ACG emissions (Bulgaria, Greece, Estonia, Slovakia and Romania need to reduce their ACG emissions) and reducing O3PR emissions (Greece, Romania, Bulgaria, Latvia, and Czech Republic).

Finally, to increase the economic performance Romania, Bulgaria, Czech Republic, Hungary, and Greece need to increase their GVA.

Still concerning the countries with lower eco-efficiency in 2014, it is interesting to highlight the worsening of Italy, Spain, Netherlands, Romania, Bulgaria, and the Czech Republic. Finally, Romania, Bulgaria and the Czech Republic require the biggest adjustments in all inputs and outputs to become efficient.

The overall adjustments prescribed by the DDF model regarding the direct consumption supply chain of the electricity sector are provided in Figures 23S to 27S (supplementary material).

4.3. Indirect consumption supply chain

Tables 15S to 18S (supplementary material) depict information on the descriptive statistics of both efficient and non-efficient DMUs in the case of the eco-efficiency assessment of the indirect consumption supply chain of the electricity

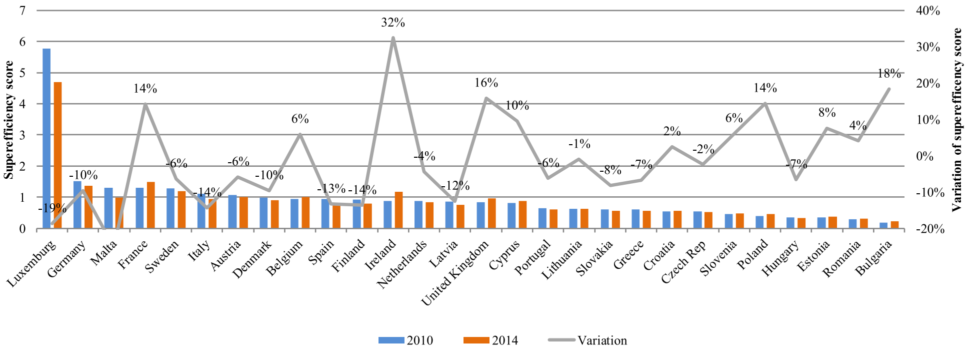

Fig. 6. Super efficiency scores in 2010 and 2014 — Indirect consumption supply chain.

sector. From the analysis of these tables, it might be established that the average super efficiency values of efficient DMUs have decreased 20% from 2010 to 2014, mainly due to a mild reduction of the environmental impacts and labour at the expense of a reduction of the GVA. In what concerns the inefficient DMUs, the average inefficiency score drops less than 1% because of the slight increase of the GVA at the cost of an also slight increase in labour, while emissions decreased.

In 2010, Table 5S (supplementary material) shows the existence of 7 efficient countries (Luxemburg, Germany, Malta, France, Sweden, Italy, and Austria) from which the three countries more frequently nominated as benchmarks regarding the indirect consumption supply chain of the electricity sector were Sweden, Luxembourg, and Austria. In 2014, Table 6S (supplementary material) also presents 7 efficient countries (Luxemburg, Germany, France, Sweden, Austria, Belgium, and Ireland) from which the top three countries mainly regarded as a reference in terms of best practices were Sweden, Luxembourg, and Ireland.

The countries with the lowest eco-efficiency performance both in 2010 and in 2014 were Bulgaria, Estonia, Hungary and Romania — Tables 5S and 6S (supplementary material).

In 2014, Malta and Italy lost their efficiency status while Belgium and Ireland became efficient – Fig. 6.

Through the analysis of the super efficiency scores attained (Fig. 6), we can conclude that apart from the countries that have become efficient, only Bulgaria, Croatia, Cyprus, Estonia, Poland, Romania, Slovenia and the United Kingdom, which stayed inefficient, and France, which remained efficient, have increased their efficiency scores.

In the case of the indirect consumption supply chain, which represents the impacts of the intermediate consumption of the sectors directly engaged with electricity sector, sector D35 plays again a major role regarding the evolution of the efficiency scores illustrated in Tables 5S and 6S (supplementary material), since all the activity sectors are extremely dependent on this sector for the production of goods and services. Due to this dependency, the evolution of environmental performance has a similar behaviour to the production chain of the electricity sector. The only country which changed its trend was Germany.

Regarding the countries that became efficient, Belgium strongly decreased its environmental impacts (with a reduction of GHG, ACG, and O3PR in 24%, 39%, and 34%, respectively) and enhanced its economic performance by 2%, while Ireland had a significant reduction of its environmental impacts (reduced GHG, ACG, and O3PR in 20%, 37%, and 33%, respectively) and a significant improvement of both economic performance (augmented GVA in 40%) and labour productivity (diminished labour in 18%). The results of Belgium are explained by an increase in renewable electricity generation of 70% and a fuel generation decrease of 37% (European Commission, 2018). Additionally, this country also shows a growth of the GVA of sector D35. Ireland in its turn enlarged the use of renewable sources for electricity generation by 71% and reduced by 21% the fossil fuel use in electricity generation (European Commission, 2018). The improvement of economic performance and labour productivity were also the responsibility of sector D35.

Then again, concerning the countries that increased their efficiency, they can be grouped into efficient and inefficient. The first group is only composed of France which significantly improved its environmental performance (decreased GHG, ACG, and O3PR in 43%, 51%, and 50%, respectively) also fostering its economic (increased GVA in 15%) and labour productivity outcomes (decreased labour in 9%) – Fig. 7. The environmental results of France are based on the fact that electricity generation from renewable sources has augmented 18% and fossil fuel electricity generation had a cut of 51% during this period of analysis (European Commission, 2018). The GVA results are explained by the variations that took place in sector D35, while labour outcomes are the result of the decrease of employed persons in all sectors of the French economy except for sector D35, which had an increase in 2014.

In the second group of countries, Bulgaria, Croatia, Cyprus, Estonia, Poland, Romania, Slovenia, and the United Kingdom had their eco-efficiency linked to an upgrade on the environmental performance by reducing GHG, ACG and O3PR emissions, which is the result of improvements in the behaviour of sector D35, explained by the reduction of 5%, 36%, 23%, 8%, 5%, 8%, 29%, and 29%, respectively, in the use of fossil fuels and by the increase of 24%, 7%, 334%, 33%, 78%, 34%, 40%, and 130%, respectively, in the use of renewable energy (European Commission, 2018).

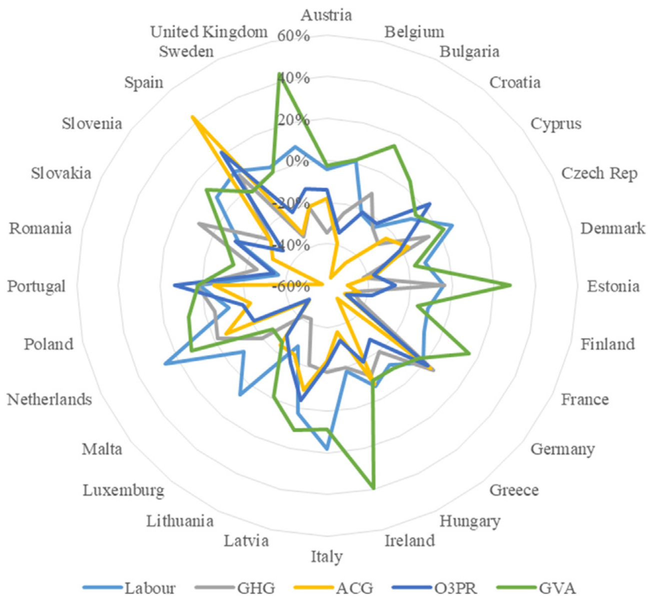

Fig. 7. Changes of inputs and outputs between 2010 and 2014 — Indirect consumption supply chain.

In what concerns the countries with lower eco-efficiency performance in 2014, the factors that seem to be sustaining this outcome, according to the projections of the DDF model, are the need to increase the average productivity of labour (Bulgaria, Latvia, Romania, Hungary and Estonia which have to reduce labour by 77%, 69%, 69%, 67%, and 63%, respectively); the environmental performance by reducing GHG emissions (Poland, Netherlands, Czech Republic, Greece and Bulgaria require a reduction of their GHG emissions by 91%, 85%, 85%, 79%, and 77%, respectively), ACG emissions (Bulgaria, Cyprus, Poland, Romania, and Greece have to reduce their ACG emissions by 95%, 94%, 93%, 92%, and 92%, respectively) and O3PR emissions (Greece, Poland, Bulgaria, Czech Republic, and Cyprus should reduce their O3PR emissions by 90%, 86%, 82%. 78% and 73% respectively).

Finally, to increase the economic performance Malta, Bulgaria, Romania, Hungary, Estonia need to increase their GVA by 301%, 77%, 69%, 67% and 63%, respectively.

Furthermore, in what concerns the countries with lower eco-efficiency, in 2014, it is interesting to point out the behaviour of Italy, Malta, Spain, Germany, Denmark, Finland, Greece, Hungary and Bulgaria. Italy became inefficient in 2014 mainly due to the mild increase of GVA at the expense of the strong increase of labour in sector D35, since its environmental performance improved (reduction of GHG in 18%, ACG in 24% and O3PR in 22%). Malta, on the other hand, became inefficient despite the reduction of environmental impacts (reduction of GHG in 20%, ACG in 49% and O3PR in 49%), since it reduced its labour productivity and decreased its GVA by 27%. Spain lost efficiency in 2014 due to the increase of its emissions (increased GHG 8%, ACG 43% and O3PR 22%), the increase of labour in 10% and the reduction of GVA by 2%. The loss of environmental performance is linked to sector D35 which augmented its emission contributions due to the use of solid fuels for electricity generation, as already mentioned (European Commission, 2018). The reduction of labour productivity and economic performance were specifically related to the increase of labour in sector N - Administrative and support service activities - and to the reduction of GVA in sector D35. Germany in its turn shows a loss of efficiency which can be linked to the rise of emissions (an increase of GHG emissions by 5%, ACG emissions by 3% and O3PR by 2%) and a reduction of GVA (-4%) mainly due to sector D35. This behaviour is consistent with the increase in carbon intensity because emissions from the electricity sector in electricity production decreased less (-2%) than the overall output of that sector (-6%) (Timmer et al., 2015). In our point of view, there are three possible reasons for this increase in carbon intensity in the electricity sector. The first reason is the phase-out of nuclear power plants whose electricity generation has not been completely complemented by renewable energies which led to the use of solid fuels (coal, lignite, …), which increased by 4%, in 2014 (European Commission, 2018). The second reason is due to the European Union Emission Trading System (EU ETS) crisis which led to the significant rollout of renewable energies in electricity generation not being compatible with emission reductions since the necessary incentives for carbon-intensive power generators were not given to reducing their emissions due to extremely low CO2 prices. With this, these producers increased their electricity exports to neighbouring countries leading to the stagnation of emission reductions in this country (European Commission, 2018; (Fabra et al., 2015). The third reason is that Germany has changed its remuneration system for renewables considering the compliance with the guidelines of the European Commission on State aid (Fabra et al., 2015). These changes were based on the shift from Feed-in-Tariffs (FiT) to premium market and direct market policies; growth corridors for renewables in which the feed-in remuneration is adjusted to the number of new installations and the national target of installed

Table 8
Top 5 increasing sectors — direct consumption supply chain.
Source: Authors' own calculations.

GHG (x1000 ton)				ACG (x1000 ton)				O3PR (x1000 ton)			
Sector	2010	2014	Variation	Sector	2010	2014	Variation	Sector	2010	2014	Variation
A01	175	279	104	A01	2	4	2	A01	1	1	0
H51	100	128	28	H51	0	0	0	H51	1	1	0
A03	3	9	6	C21	0	0	0	C10–C12	0	0	0
H52	44	48	5	U	0	0	0	C21	0	0	0
H49	1125	1128	3	T	0	0	0	C13–C15	0	0	0

capacity; setting a cap for new installations of photovoltaics (PV) and reduction of feed-in remuneration; reduction in the incentives for Biomass; and changes in renewable energy surcharge, ending with several excessive exceptions (Appunn, 2014). Denmark, Finland Greece, and Hungary have their loss of efficiency linked to the reduction of the GVA provided by sector D35. Finally, Bulgaria is in the top five countries that require adjustment in all its inputs and outputs.

The overall adjustments prescribed by the DDF model regarding the indirect consumption supply chain of the electricity sector are provided in Figures 28S to 32S (supplementary material).

4.4. Variations in terms of contributions of emissions for the electric sector

In order to understand how the electricity sector is influenced in terms of environmental impacts, it is necessary to know which sectors increased and reduced, both directly and indirectly, their contributions and which countries have the main role in this behaviour.

Through the analysis of Table 8 it is possible to observe that the sectors with the biggest direct contribution to the increase of emissions in the electricity sector were A01, H51 — Air Transport, A03 — Fishing and aquaculture, H52 — Warehousing and support activities for transportation and H49. In this context, Italy increased the majority of its emissions in all sectors except for sectors H49 and H52. It is also worth mentioning that Italy leads the emission contributions from sector A01, which can be related to the fact of this country occupying the 3rd place in terms of the amount of electricity generated from biomass in 2014, with an increase of 98% since 2010 (European Commission, 2018).

After analysing the results of Table 9, it can be noted that the sectors with the highest direct impact on the reduction of emissions in the electricity sector were sectors D35, B, E37–E39, C19 and C20 — Manufacture of chemicals and chemical products. Additionally, the countries that significantly reduced the emission contributions to the electricity sector were the United Kingdom, followed by France and Germany (which is the biggest producer of emissions resulting from the fact of being the biggest energy consumer of the UE28). Also, France remained as one of the biggest reducers in emissions in the remaining sectors of Table 9 due to its electricity production structure (77% Nuclear; 18% Renewables) and based on a reduction of 51% in fossil fuels usage (European Commission, 2018), while Germany is the country that mostly decreased its emissions in sector B, followed by the United Kingdom which shared the first place of direct emissions produced by this sector with Poland, since the former is one of the biggest producers of natural gas in Europe, while the latter plays a major role in the production of coal (Brown et al., 2016).

Another interesting fact regarding Germany is its first place in emission contributions from sectors C23 — Manufacture of glass and glass products, cement and other non-metallic minerals and C24 — Manufacture of basic metals (iron and steel), which are sectors linked to the construction of the components of wind turbines. Moreover, Germany has been the largest producer of the European Union in this field (EU-MERCI, 2012). These findings can be related to the fact that Germany is the biggest wind power player of EU28 since it is the country with the largest wind power installed capacity and with the highest amount of electricity generated from this renewable source (European Commission, 2018).

The emissions produced by sectors E37–E39 are led by Italy, which reduced in 2014, and are related to its 3rd place in electricity generation from biogas in EU28, mostly from anaerobic digesters (Scarlat et al., 2018).

Finally, the emissions produced by sector C19 are led by Spain, which increased in 2014, being the biggest electricity producer using petroleum products in UE28 alongside with Italy (European Commission, 2018), while France leads the emission contributions of sector C20 due to its leading role in the chemical industry, representing the second-largest producer in Europe and the sixth in the world, respectively.

Table 10 allows us to point out that the sectors which mostly contribute indirectly for increasing the emissions of the electricity sector were A01, H51, A03, C26 — Manufacture of computer, electronic and optical products and U - Activities of extraterritorial organizations and bodies. In this case, Italy presents the biggest increase in emissions in sectors A01 (following the same justification of the direct consumption supply chain) and H51, while Slovakia occupies the first place in sector A03.

After analysing the results of Table 11, it is possible to observe that the sectors that highly contributed indirectly to the reduction of emissions in the electricity sector were D35, B, C23, E37–E39, and C20. In this situation, France presents the highest emission reduction in all sectors. The other countries with the larger declines in terms of emissions of the sectors presented in Table 11 were Italy, in sector C23; Spain, in sector B; the United Kingdom in sector D35; Cyprus, in sectors

Table 9
Top 5 decreasing sectors — direct consumption supply chain.
Source: Authors' own calculations.

GHG (x1000 ton)				ACG (x1000 ton)				O3PR (x1000 ton)			
Sector	2010	2014	Variation	Sector	2010	2014	Variation	Sector	2010	2014	Variation
D35	82929	70913	−12016	D35	188	137	−51	D35	150	125	−25
B	5244	4222	−1023	B	9	6	−2	B	26	23	−3
E37–E39	875	698	−177	C19	4	2	−2	H49	9	8	−2
C19	928	787	−141	H49	4	4	−1	C19	3	2	−1
C20	336	259	−77	C20	1	1	0	E37–E39	2	1	0

Table 10
Top 5 increasing sectors — indirect consumption supply chain.
Source: Authors' own calculations.

GHG (x1000 ton)				ACG (x1000 ton)				O3PR (x1000 ton)			
Sector	2010	2014	Variation	Sector	2010	2014	Variation	Sector	2010	2014	Variation
A01	458	536	78	A01	7	9	1	H51	1	1	0
H51	207	237	30	H51	1	1	0	A01	3	3	0
A03	7	12	5	U	0	0	0	C10–C12	0	0	0
C26	2	2	0	T	0	0	0	C13–C15	0	0	0
U	0	0	0	A03	0	0	0	U	0	0	0

Table 11
Top 5 decreasing sectors — indirect consumption supply chain.
Source: Authors' own calculations.

GHG (x1000 ton)				ACG (x1000 ton)				O3PR (x1000 ton)			
Sector	2010	2014	Variation	Sector	2010	2014	Variation	Sector	2010	2014	Variation
D35	504322	451989	−52334	D35	1283	915	−368	D35	872	731	−141
B	2324	1827	−497	H49	5	4	−1	H49	10	7	−3
C23	976	780	−196	B	5	4	−1	B	15	13	−1
E37–E39	888	733	−155	C19	3	2	−1	C23	3	2	−1
C20	395	292	−103	C23	3	2	−1	C24	2	1	0

E37–E39; and, Germany, in sector C20. It is also essential to mention that Germany, the United Kingdom, Italy, and France occupy the first place in indirect emission contributions from sectors D35 and C23, B, E37–E39, and C20, respectively. The first place of Germany in sector D35 is related to its electricity consumption, which is the biggest in EU28, while its first place in sector C23 is related to the manufacture of components for the manufacture of wind turbines. The first place of the United Kingdom in sector B is related to the production of natural gas as already mentioned. Finally, Italy's first place in sectors E37–E39 is related to the third- place it occupies in electricity generation from biogas in EU28. Finally, the first place of France in sector C20 is related to its role in the chemical industry.

5. Conclusions

This work established a methodological framework that allows performing an eco-efficiency assessment of the electricity sector in EU28 considering the economic and environmental performance of this sector over the years of 2010 and 2014.

The approach followed involved combining the DEA methodology through the DDF approach with IO analysis. The use of the DEA model allows overcoming one of the main challenges faced in the sustainability assessment of the electricity sector by encompassing into a single score metrics consistent with distinctive concerns, specifically incorporating as inputs the labour and capital stock, as bad outputs GHG emissions, ACG emissions and O3PR, and as good outputs the contribution of the electricity sector to GVA. Through the use of this methodology, it is also possible to identify which countries are used as benchmarks in terms of best practices for the inefficient countries, also suggesting the required adjustments (i.e. the increase of GVA and the average productivity of labour and capital, and the decrease of the environmental impacts) regarding the inefficient countries. Besides, this particular feature of the model is useful to shed light on the policies that should be fostered to reach efficiency.

The use of the IO methodology enables performing an enhanced eco-efficiency assessment, since, in addition to the evaluation of the direct production chain, it also comprehends in the analysis the direct and indirect consumption supply chains, using sector D35 as a proxy for the electricity sector. Finally, through the use of this latter approach, it is also possible to ascertain which sectors increased and reduced, both directly and indirectly, their contributions to the eco-efficiency of the electricity sector and which countries have the main role in this behaviour.

Our findings suggest that the average emissions in the direct production chain as well as in the direct and indirect consumption supply chains have decreased from 2010 to 2014, although the GVA was higher on average. These results were consistent with the increase of renewable energy sources (31%) and the reduction of fossil fuel (20%) that took place in electricity generation in EU28.

In what concerns the direct production chain we were able to witness that the efficiency scores decreased, due to a slight reduction of the GVA and a mild increase of capital in the efficient countries and because of the rise of GVA at the expense of a larger percentage growth of capital in the remaining cases, even though in both situations the emissions suffered a reduction. The increase of the stock of capital can be explained by the 40% growth in the renewable electricity installed capacity, whereas the installed capacity of fossil fuels and nuclear power reduced 1% and 6%, respectively. The countries more frequently considered as benchmarks in 2010 were Malta, Germany, and Belgium, whereas in 2014 these countries were Ireland, France, Malta, and Luxemburg. The countries with the lowest efficiency scores in this time frame were Hungary, Estonia, Slovakia, and Slovenia. Regarding the countries that increased their efficiency scores in 2014, we were able to identify Poland, the Netherlands, the United Kingdom, France, Belgium, Ireland, Portugal, and Bulgaria. All those countries turned their electricity generation more eco-efficient by replacing fossil fuel generation with renewable energy sources. In the opposite direction, we found Austria, Cyprus, and Latvia which became inefficient in 2014.

In the case of the direct consumption supply chain, the superefficiency score grew mainly due to Cyprus and also because of a significant increase in labour productivity and a reduction of emissions at the expense of a small reduction of the GVA. On the other hand, in what concerns the inefficient countries, the efficiency score decreased due to an increase in the GVA at the cost of a reduction in environmental performance. In this assessment, we were able to find that the top three countries considered as benchmarks in 2010 were Luxemburg, Denmark, and Sweden and, in 2014, Luxemburg was supplanted by Cyprus.

Finally, the lowest efficiency scores in this period were reached by Bulgaria, the Czech Republic, and Romania. From 2010 to 2014, Italy was the only country that became inefficient, whereas Ireland, and Malta, become efficient in 2014. Additionally, the countries which increased their eco-efficiency were Croatia, Estonia, Finland, Greece, and Lithuania, that remained inefficient, and Belgium, Cyprus, France, and the United Kingdom, that remained efficient. The top five sectors with the highest direct contribution to the electricity sector emissions were, in decreasing order of importance, D35 (which stands out from the following sectors by the way it influences the country's emissions), B, H49, C19, and E37–E39.

The top five sectors with the biggest indirect contribution to pollutant emissions in the electricity sector were the same as the ones attained in the direct consumption supply chain with an exception: sector C19 is replaced by sector C23. In this latter case, the importance of sector D35 is even bigger because all sectors are directly linked to it. Therefore, the renewable generation of electricity plays a major role in eco-efficiency. The only country that reversed this trend was Germany, since its emissions increased in 2014, as a result of the increase in the carbon intensity of the electricity sector due to the phase-out of nuclear power plants whose electricity generation has not been completely complemented by renewable energies leading to the increase of the use of solid fuels in 2014. Furthermore, the EU ETS crisis led to the significant rollout of the renewable energies in electricity generation resulting in the stagnation of emission reductions (European Commission, 2018; Fabra et al., 2015); and there was a change of State aid policies in the remuneration system for renewables (Appunn, 2014; Fabra et al., 2015).

Taking into consideration the direct production chain and the direct and indirect consumption supply chains, it can be concluded that the only countries that increased their efficiency scores were France (the only efficient country which increased its efficiency), Ireland (the only country that became efficient in all chains), the United Kingdom and Belgium. It is worth mentioning that the countries which were efficient across all chains, both in 2010 and 2014, were France, Luxemburg, Germany and Sweden while Poland, the Netherlands, Estonia (the only country in the top four lowest efficiency scores in all chains), Hungary, Croatia, Finland, Lithuania, Slovakia, the Czech Republic, Slovenia, and Greece were inefficient.

As it can be seen through this study, the countries that invested more in renewable energy deployment efficiently, progressively replacing fossil fuel generation, increased their potential in terms of eco-efficiency by reducing the emissions produced by the electricity sector and stimulating the growth of value-added created by it. In this sense, it can be concluded that renewable energy sources present a threefold solution to this problem. Firstly, because electricity production from renewable sources reduces the need for fossil fuels and therefore promotes a significant reduction of emissions. Secondly, renewable technologies already have a degree of maturity that leads to a decrease in the value of investment, making the cost of electricity production much lower. Lastly, with the production of electricity through renewables, there will be an ever-decreasing need for the imports of fossil fuels, thus leading to a reduction in electricity prices as well.

With this regard, we provide below some political recommendations for decision-makers to promote the growth of eco-efficiency of the EU28 electricity sector. In this context, the policies adopted should:

- Reinforce the carbon signal beyond the present emission trading system (EU ETS) - due to the economic crisis and the rapid expansion of renewables, the EU ETS has delivered wrong signals by giving prices too low and volatile to affect the investor's decisions in a meaningful manner towards the adoption of renewable energy technologies. Indeed, from 2011 to 2012 the weight of coal-fired generation has grown 13% because the prices of solid fuels remained under 10€/Ton instead of being above 30€-40€ per Ton (Fabra et al., 2015). An example of success is Sweden which firstly introduced a carbon tax in 1991 with a value of 24€ per ton of CO2 and in 2019 achieved 114€ per ton of CO2 (Åkerfeldt et al. 2019).

- Strengthen cooperation between countries in order to promote a unique European electricity market. This can help the countries with lower capacity for reducing their emissions in the power sector, facilitating the energy transition, avoiding the loss of productivity and stimulating the decrease of the electricity prices, the decrease of fossil fuels use, ensuring the security of supply and the decrease of the competitiveness of fossil fuels;
- Intensify the rules applied in order to achieve stringent renewable energy targets. Through this, countries become more motivated to change their energy matrix;
- Promote research and development in order to redesign policies and promote the innovation of technologies;
- Foster regulatory stability for keeping investments without risk for investors;
- Guarantee that electricity assets produce suitable revenues enabling capital suppliers to be adequately compensated for the risks taken;
- Create ministries of energy governed by specialized people in order to promote the most suitable policies for renewable energy deployment;
- Impose quota obligations like Renewable Purchase Obligation (RPO) or Renewable Portfolio Standards (RPS) that oblige stakeholders to introduce a certain amount of renewable energy sources in their energy matrix (IRENA, OECD/IEA, & REN21, 2018);
- Establish renewable electricity certificates, which award generators for megawatt of renewable energy produced. These certificates can be purchased by the stakeholders for meeting their obligations;
- Administratively set feed-in policies like feed-in premium (FiP) and auctions. The FiP can be used in distributed generation to leverage small projects like self-consumers or PV in buildings, implementing a floor and a cap to reduce the risk of losses or windfall profits. Auctions on their hand, can be used for large projects ensuring more transparency for investors and helping to discover the prices of the technology in bidding;
- Foster Net Metering and Net Billing in distributed generation. The former, offers compensation in credits of kWh to the producer while the latter offers a monetary compensation for kWh exported to the grid (IRENA, OECD/IEA, & REN21, 2018). With a suited and well-developed smart grid, the net billing will increase the potential of distributed generation offering to the prosumers the possibility to self-consume energy and export the excess to the utility grid. With a mature distributed generation scheme in place, the prices could be changed in order to shift consumption for periods where the renewable generation is more abundant and giving a proper compensation for producers in those periods;
- Set fiscal and financial incentives coupled with strict monitoring and harsh penalties for controlling corruption or failures with agreed contractual assumptions in renewable energy generation;
- Promote awareness programs on the renewable energy benefits for population aimed to educate consumers for the benefits of renewable energy for economic development, GHG emission reduction, air-quality improvement. These programs are aimed at encouraging the investment in renewables, enabling the expansion of distributed generation and corporate procurement (in which many companies incorporate voluntarily an increase level of renewable energy sources in their supply chain) (IRENA, OECD/IEA, & REN21, 2018).

Despite the main novelty of this work can be seen as a breakthrough in the study of the eco-efficiency of the electricity sector for EU-28, some limitations can be identified, namely due to the lack of comparability of our results with other studies. Another limitation of this study refers to the fact of leaving the nuclear wastes unattended.

Future work should contemplate the analysis of the evolution of the eco-efficiency of the electricity sector in the several EU countries to the present date and to compare it with our findings, also evaluating which countries have best adapted to the needs of decreasing their inputs and increasing outputs and which policies had the most responsibility in this evolution.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Identification of the activity sectors

See Table A.1

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eap.2020.05.003.

Table A.1
Identification of the activity sectors belonging to the consumption supply chain of the electricity sector.

Identification of the activity sectors
A01 — Crop and animal production, hunting and related service activities
A02 — Forestry and logging
A03 — Fishing and aquaculture
B - Mining and quarrying
C10–C12 — Manufacture of food products, beverages and tobacco products
C13–C15 — Manufacture of textiles, wearing apparel and leather products
C16 — Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
C17 — Manufacture of paper and paper products
C18 — Printing and reproduction of recorded media
C19 — Manufacture of coke and refined petroleum products
C20 — Manufacture of chemicals and chemical products
C21 — Manufacture of basic pharmaceutical products and pharmaceutical preparations
C22 — Manufacture of rubber and plastic products
C23 — Manufacture of other non-metallic mineral products
C24 — Manufacture of basic metals
C25 — Manufacture of fabricated metal products, except machinery and equipment
C26 — Manufacture of computer, electronic and optical products
C27 — Manufacture of electrical equipment
C28 — Manufacture of machinery and equipment n.e.c.
C29 — Manufacture of motor vehicles, trailers and semi-trailers
C30 — Manufacture of other transport equipment
C31_C32 — Manufacture of furniture; other manufacturing
C33 — Repair and installation of machinery and equipment
D35 — Electricity, gas, steam and air conditioning supply
E36 — Water collection, treatment and supply
E37–E39 — Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services
F – Construction
G45 — Wholesale and retail trade and repair of motor vehicles and motorcycles
G46 — Wholesale trade, except of motor vehicles and motorcycles
G47 — Retail trade, except of motor vehicles and motorcycles
H49 — Land transport and transport via pipelines
H50 — Water transport
H51 — Air transport
H52 — Warehousing and support activities for transportation
H53 — Postal and courier activities
I - Accommodation and food service activities
J58 — Publishing activities
J59_J60 — Motion picture, video and television program production, sound recording and music publishing activities; programming and broadcasting activities
J61 — Telecommunications
J62_J63 - Computer programming, consultancy and related activities; information service activities
K64 — Financial service activities, except insurance and pension funding
K65 - Insurance, reinsurance and pension funding, except compulsory social security
K66 - Activities auxiliary to financial services and insurance activities
L68 - Real estate activities
M69_M70 - Legal and accounting activities; activities of head offices; management consultancy activities
M71 - Architectural and engineering activities; technical testing and analysis
M72 - Scientific research and development
M73 - Advertising and market research
M74_M75 - Other professional, scientific and technical activities; veterinary activities
N - Administrative and support service activities
O84 - Public administration and defense; compulsory social security
P85 – Education
Q - Human health and social work activities
R_S - Other service activities
T - Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
U - Activities of extraterritorial organizations and bodies

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