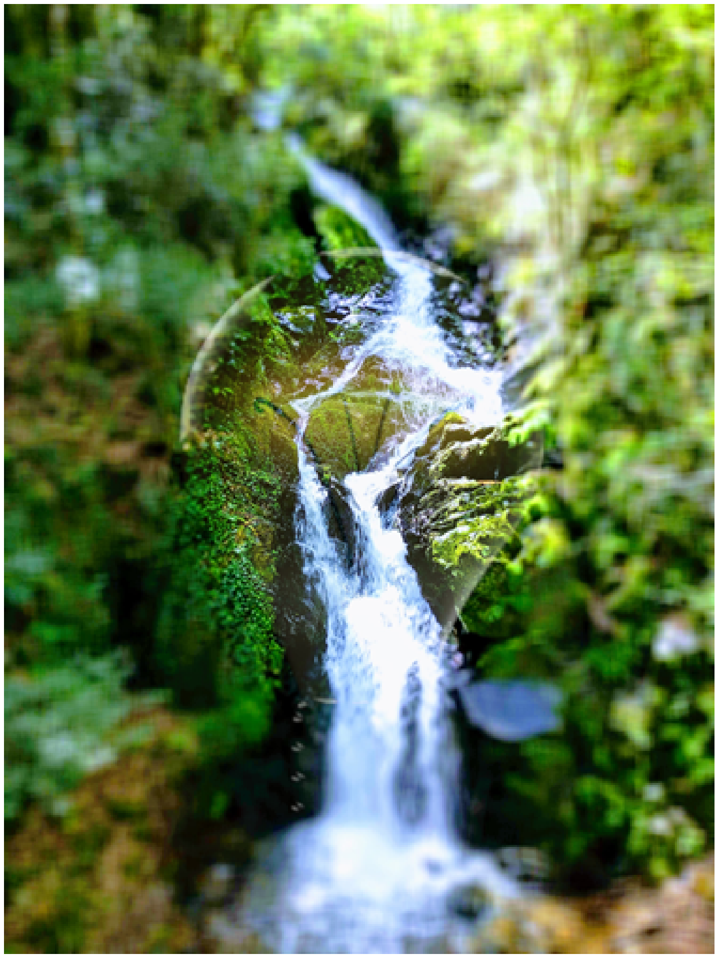

Marcos Daniel Nujo Tenente

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

Master's Dissertation in Energy for Sustainability
Specialization in Energy Systems and Policy
Supervised by Professor Patrícia Pereira da Silva and Professor Carla Margarida Saraiva Oliveira Henriques

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ENERGY FOR SUSTAINABILITY - EFS

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

MASTER'S DISSERTATION IN ENERGY FOR SUSTAINABILITY DEVELOPED UNDER THE SPECIALIZATION OF ENERGY SYSTEMS AND POLICY FOR THE AWARD OF THE MASTER OF SCIENCE (M.SC.) DEGREE.

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“Success consists of going from failure to failure without loss of enthusiasm”

Winston Churchill

RESUMO

O objetivo deste estudo consistiu na avaliação da ecoeficiência do sector elétrico nos 28 países da União Europeia, tendo em consideração o seu desempenho económico e ambiental ao longo do tempo, considerando os anos de 2010 e 2014 como anos de base. A principal novidade introduzida neste estudo reside na combinação da utilização da Analise Envoltória de Dados através da Função de Distância Direcional com a análise *Input-Output*, para realizar a avaliação da ecoeficiência das cadeias de fornecimento e de consumo do sector elétrico. De acordo com os resultados obtidos, os três países mais frequentemente selecionados como referência em relação à cadeia produção direta do sector elétrico foram, em 2010, Malta, Alemanha e Bélgica; enquanto, em 2014, os quatro países principalmente considerados como referência em termos de melhores práticas foram a Irlanda e França, seguidos por Malta e Luxemburgo. Uma vez que o tipo de eficiência em análise não é apenas económico, mas também ambiental, é expectável que os países que investiram eficientemente na instalação de energia renovável, substituindo progressivamente a geração por combustíveis fósseis, tenham tido um maior potencial em termos de ecoeficiência. Por exemplo, no caso de Portugal, Irlanda e Bulgária, a melhoria do desempenho da ecoeficiência parece ser resultado da melhoria das produtividades médias do capital e o do trabalho, da redução da geração com base em combustíveis fósseis e de um aumento da geração de energia renovável. Na avaliação da eficiência da cadeia de fornecimento do consumo direto, os três países vistos mais frequentemente como referência, em 2010, foram o Luxemburgo, Dinamarca e Suécia, enquanto, em 2014, os três países principalmente selecionados como referência, em termos de melhores práticas, foram a Dinamarca, seguida pelo Chipre e Suécia. Neste caso, a evolução dos sectores diretamente ligados ao sector elétrico contribuiu para os resultados de eficiência obtidos. Finalmente, quando a cadeia de fornecimento de consumo indireto foi avaliada, constatou-se que os três países mais frequentemente selecionados como referência foram, em 2010, a Suécia, o Luxemburgo e a Áustria; enquanto, em 2014, os três principais países estabelecidos como *benchmark* foram a Suécia, o Luxemburgo e a Irlanda. Nesta última situação, o principal determinante para os níveis de eficiência obtidos foi o consumo intermédio dos sectores indiretamente ligados ao sector elétrico.

Palavras-chave: Análise Envoltória de Dados; Função de Distância Direcional; Avaliação da Ecoeficiência; Sector Elétrico; União Europeia.

ABSTRACT

The purpose of this study is to carry out the eco-efficiency assessment of the electricity sector in 28 European Union countries, taking into account its economic and environmental performance over time, considering the years of 2010 and 2014. The novelty of our work resides in the combination of Data Envelopment Analysis through the Directional Distance Function approach 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 three countries more frequently selected as benchmarks regarding the direct production chain of the electricity sector were, in 2010, Malta, Germany and Belgium, while, in 2014, the top four countries mainly considered as a reference in terms of best practices were Ireland and France followed by Malta and Luxembourg. Since the type of efficiency under analysis is not only economic, but also environmental, it is expected that countries who 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, Ireland and Bulgaria, 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 increase of renewable energy generation. In the efficiency assessment of the direct consumption supply chain, the three countries more often nominated as benchmarks in 2010 were Luxembourg, Denmark and Sweden, whereas, in 2014, the top three countries mainly viewed as a reference in terms of best practices were Denmark followed by Cyprus and Sweden. In this case, the evolution of the sectors directly linked to the electricity sector were the main drivers of the efficiency scores obtained. Finally, when the indirect consumption supply chain was evaluated, it was found that the three countries more often selected as benchmarks were, in 2010, Sweden, Luxembourg and Austria, while, in 2014 the top three countries mainly established as a reference were Sweden, Luxembourg and Ireland. In this last situation, the main determinant for the efficiency scores is the intermediate consumption of the sectors indirectly engaged with the electricity sector.

Keywords: Data Envelopment Analysis; Directional Distance Function; Eco-efficiency assessment; Electricity Sector; European Union.

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ABBREVIATIONS

ACG - Acidifying Gases

BCC model - Banker, Charnes and Cooper model

BO - Bad Outputs

CCR model - Charnes, Cooper and Rhodes model

CRS - Constant Return Scale

CSC - Consumption Supply Chain

CSCIIDC - Consumption Supply Chain Indirect Impacts Direct Coefficients

CSCIIIC - Consumption Supply Chain Indirect Impacts Indirect Coefficients

DC - Direct Coefficients

DDF - Directional Distance Function

DEA - Data Envelopment Analysis

DI - Direct Impacts

DMU - Decision Making Unit

DPC - Direct Production Chain

DPCDI - Direct Production Chain Direct Impacts

EEIO - Environmental Extended Input-Output

ETS - Emissions Trading System

EU28 - 28 countries of European Union

FiP - Feed-in Premium

FiT - Feed-in Tariffs

GHG - Greenhouse Gases

GI - Good Inputs

GO - Good Outputs

GVA - Gross Value Added

IC - Indirect Coefficients

II - Indirect Impacts

IO - Input-Output

K - Capital

LP - Linear Programming

O3PR - Ozone Precursors

OECD - Organisation for Economic Co-operation and Development

PV - Photovoltaic

REC - Renewable Energy Certificates

RPO - Renewable Purchase Obligations

RPS - Renewable Portfolio Standards

SBM - Slack Based Measure

1. Introduction

Currently, it is anticipated that, if everyone in the world consumes as many natural resources as the average European citizen, humanity would need two planets' worth of natural resources by 2050 (Sáez-Martínez, et al., 2016; Worldwide Fund for Nature, 2015). Furthermore, according to the Intergovernmental Panel on Climate Change (IPCC, 2018) it is vital to limit the rise of global temperature below 1.5 degrees Celsius, compared with pre-industrial levels. In order to achieve this purpose the CO2 emissions have to decline about 45% from 2010 levels by 2030 and reach net zero by 2050. Therefore, it is imperative to significantly reduce the consumption of fossil fuels and consequently greenhouse gas (GHG) emissions. In this regard the EU economic policy brought to the policy agenda the promotion of economic growth, but specifically encompassing the reduction of GHG emissions, making eco-efficiency an issue of the utmost importance (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 sustainability in that it takes into account only environmental and economic aspects leaving the social dimension out. Eco-efficiency is 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 the last is the ratio between desirable outputs and inputs, disregarding ecological aspects.

Nevertheless, the appraisal of the environmental footprint of an economy presents a challenging endeavour since it requires the evaluation of the environmental impacts that are embodied in goods and services traded between economic sectors. In this context, the use of Input-Output (IO) tables is particularly suited, since it allows broadening the scope of analysis enabling the incorporation of environmental impacts which are linked with a wide range of economic transactions between different activity sectors. These tables are also known as Environmental Extended Input-Output (EEIO) tables. Previous efforts which focused on studying the aggregate impacts of economic regions considering both production and consumption patterns failed to analyse eco-efficiency. Instead, these studies often performed their evaluation of environmental and economic performances independently (Zurano-Cervelló, et al. 2018).

Presently, there is an increasing research interest regarding the efficiency level of utility operations, along with environmental impacts of the electricity production chain (Sueyoshi and Goto, 2018). Therefore, the popular application of Data Envelopment Analysis (DEA) in the assessment of the electricity sector has resided in the need of improving its efficiency both in the transmission and distribution networks and in generation. On the one hand, transmission and distribution network interests are often linked to regulation because these two elements of the electricity value chain remain regulated due to their behaviour as monopolies. On the other hand, generation, which belongs to the competitive segment of the now liberalized electricity industry, has been experiencing an increasing number of environmental challenges.

The research interest regarding the efficiency of the electricity sector is expected to keep growing due to the fact that this sector is one of the biggest GHG emitters, which is expected to rise in view of the increasing demand for energy.

However, two major drawbacks exist 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 (see e.g. Korhonen and Luptacik (2004); Gómez-Calvet et al. (2014)); setting aside other relevant impacts such as economic and social, also disregarding the separation of the production and consumption chains of the electricity sector. Secondly, 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 the empirical evaluation in 28 EU countries through the use of EEIO tables in conjunction with DDEA, considering the years of 2010 and 2014.

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 through the use of DEA models while Zurano-Cervelló et al. (2018) combined 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 work 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.

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

Reference	***Description***	***Application***	***Inputs***	***Outputs***	***Models***
Korhonen and Luptacik (2004)	Technical efficiency and Eco-efficiency analysis of power plants	24 power plants in the EU	Total costs	Electricity generation; Dust; NO_x and SO_2 emissions	CCR (Charnes et al. 1978)
Vaninsky (2009)	Environmental efficiency	Electricity power industry in the United States (1990 - 2006)	CO_2 emissions; 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; Nº of Employees; Coal, oil and LNG	Electricity Generation; CO_2 emissions	DEA non-radial measurement - RAM (Range-Adjusted Measure); Kruskal–Wallis rank sum test
Bai-Chen et al. (2012)	Eco-efficiency assessment of generation and grid corporations	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)	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); Total-factor energy efficiency
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_x emissions; Soot.	SBM; Total-factor energy efficiency
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_2 emissions; Radioactivity	DDF; SBM

Reference	*Description*	*Application*	*Inputs*	*Outputs*	*Models*
Arabi et al., (2015)	Method to overcome the infeasibility problem of mixed periods.	Electricity sector in Iran (2003 - 2010)	Installed capacity; Fuel Consumption	Power generated; SO_2; NO_x; and CO_x emissions; Operational availability; Deviation from generation plan.	SBM; DDF; Malmquist-Luenberger index
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 Malmquiste Luenberger index; SBM
Ewertowska et al. (2016).	Environmental performance (eco-efficiency)	Electricity mix of the top 27 European economies.	Acidification; Climate change; Eutrophication; Aquatic eco-toxicity; Sediment eco-toxicity; Human toxicity; Ionising radiation; Land use; Malodorous air; Photochemical oxidation; Resources antimony; Stratospheric ozone; Terrestrial eco-toxicity	Production of 1 kWh	Lifecycle analysis (LCA); CCR
Halkos and Polemis (2018)	Environmental efficiency	Electricity sector in the United States (2001, 2002 and 2003)	Total energy transmission; Total operating costs	Utilization of net capacity; CO_2; SO_2 and NO_x emissions.	Window DEA (W-DEA); Hybrid model; Parametric and non-parametric econometric technique

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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 Figure 1.

The first step consisted in the construction of the EEIO tables for each country both for 2010 and 2014, by combining the use of National IO tables with Social Accounting and Air Emissions Accounting tables. Subsequently, in the direct production chain the direct impacts of the electricity sector are identified by using as inputs and outputs the direct values of the Social Accounting and Air Emissions Accounting tables. In the consumption supply chain the indirect impacts of the electricity sector are identified by using the IO multipliers as inputs and outputs. The direct coefficients will represent the impacts that the sectors directly linked to the electricity sector have on this sector, while the indirect coefficients, in its turn, represent the indirect impacts.

In the second step, we run the DEA model to evaluate the eco-efficiency of each decision making unit (DMU) under assessment, which in this study corresponds to each of the EU28 countries, which are then classified into inefficient ($\beta_o > 0$) and efficient ($\beta_o = 0$), depending on their efficiency scores. If the DMUs are efficient, then we run the superefficiency model to rank the efficient countries and then also compute the number of times these countries are used as benchmarks for inefficient DMUs. If the DMUs are inefficient, the DEA model gives us, in addition to its scores, the input reductions and output increases that they must undertake in order to become efficient.

Finally, based on the scores obtained, suggestions are made to improve the eco-efficiency of inefficient countries.

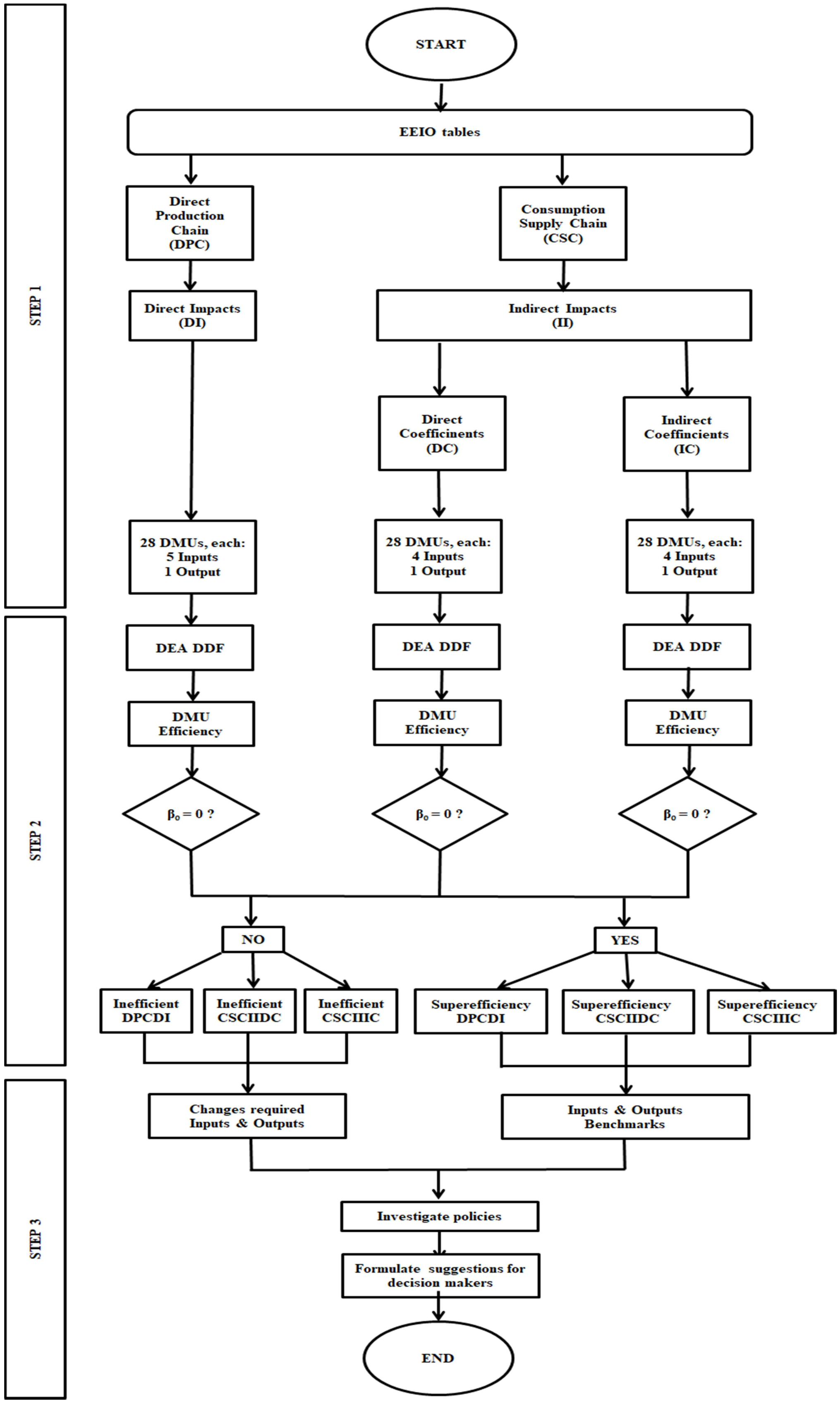

Figure 1. Diagrammatic illustration of the methodological framework used

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).

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 the direct and indirect effects.

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

$$\mathbf{x} = A\mathbf{x} + \mathbf{y}, \tag{1}$$

where A is the technological coefficient 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 coefficient matrix, E, where each component, ekj, corresponds to the quantity of energy (or to the amount of 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:

$$\mathbf{e} = E\mathbf{x}, \tag{2}$$

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 (1) and (2), $E\,(I - A)^{-1}$ can be regarded as the matrix of total energy usage coefficients, such that:

$$\mathbf{e} = E\,(I - A)^{-1}\mathbf{y} \tag{3}$$

In fact, each component of this matrix provides the energy used (pollutants emitted) per monetary unit of final demand.

2.2. The DDF approach

Charnes et al. (1978) paved the grounds for 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. 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 comprehensive efficiency assessment and allows incorporating the weak disposability assumption (i.e. that changes in the values of an undesirable factor have an impact on the value of a desirable factor).

Fukuyama and Weber (2009) suggested a measure of inefficiency also known as the directional slacks-based inefficiency (SBI) measure in order to obtain a generalized measure of technical inefficiency which considered all slacks in input and output constraints. This measure allows obtaining the same information provided by the slacks based measure (SBM) model suggested by Tone (2001) as long as the directional vectors for inputs and outputs are considered to be equal to the corresponding input and output vectors, being also regarded as a generalization of the Russell’s measure of efficiency. More recently, Färe and Grosskopf (2010) also suggested a generalization of the SBM based on the directional distance function, where the optimization problem is based on the sum of the directional distance function being able to express how much inputs have excessively been used and how much shortage of outputs have been produced regarding their efficiency level. The directional distance function aiming to increase the outputs and decrease the inputs directionally can be defined as:

$$sup\{\rho: (\boldsymbol{x} - \beta \boldsymbol{g}_x, \boldsymbol{y} + \beta \boldsymbol{g}_y) \in T\} \tag{4}$$

where the non-zero vector $\boldsymbol{g} = (-\boldsymbol{g}_x, \boldsymbol{g}_y)$ establishes the "directions" in which inputs and outputs are scaled, and the technology reference set satisfies the assumptions $T = \{(\boldsymbol{x}, \boldsymbol{y}) : \boldsymbol{x} \text{ can produce } \boldsymbol{y}\}$ of Constant Returns to Scale (CRS) (Chen, Yu, Chang, Hsu, & Managi, 2015).

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

$$T = \{(\boldsymbol{x}, \boldsymbol{y}) : \sum_{j=1}^{n} \lambda_j y_{rj} \geq y_r,\ r = 1,\ldots, s,$$
$$\sum_{j=1}^{n} \lambda_j x_{ij} \leq x_i,\ i = 1,\ldots, m,$$
$$\lambda_j \geq 0, j = 1, \ldots, n\}, \qquad (5)$$

In what regards the reference technology T considered in (5), traditionally, for each DMU under assessment, DMU_o, the directional distance function can be obtained by solving the following LP problem:

$$\max\ \beta_o$$
$$\text{s.t. } \sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{ro} + \beta_o g_{yr},\ r = 1,\ldots, s,$$
$$\sum_{j=1}^{n} \lambda_j x_{ij} \leq x_{io} - \beta_o g_{xi},\ i = 1,\ldots, m,$$
$$\lambda_j \geq 0\ (\forall_j) \qquad (6)$$

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 in order to become efficient.

In order to account for variable returns to scale (VRS) it is only necessary to add the constraint $\sum_{j=1}^{n} \lambda_j = 1$ into model (6).

Besides being a generalization of the Shephard's distance functions, the directional distance function can be specified to embed different assumptions. If $\boldsymbol{g} = (-\boldsymbol{g}_x, \boldsymbol{g}_y)$= $(-\boldsymbol{x}^o, \boldsymbol{y}^o)$, i.e., the direction is set to account for the observed data, β_o corresponds to the potential proportional variation in outputs and inputs. If alternatively $\boldsymbol{g} = (-\boldsymbol{g}_x, \boldsymbol{g}_y)$= $(-1, 1)$, then the solution value can be viewed as the net improvement in performance in terms of feasible enlargement in outputs and feasible reduction in inputs (Färe & Grosskopf, 2004).

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 firstly 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 from the set of DMUs. In order to rank the efficient DMUs the following problem should thus be solved:

max β_o

s.t. $\sum_{j\neq o}^{n} \lambda_j y_{rj} \geq y_{ro} + \beta_o g_{yr}$, $r = 1,\ldots, s$,

$\sum_{j\neq o}^{n} \lambda_j x_{ij} \leq x_{io} - \beta_o g_{xi}$, $i = 1,\ldots, m$,

$\sum_{j\neq o}^{n} \lambda_j = 1$, $\lambda_j \geq 0$ $(\forall_j)$, (7)

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.

In general, two important disposability technologies for undesirable factors are considered: one is based on strong disposal technology and the other one is based on weak disposal technology (i.e. changes in the values of an undesirable factor have an impact on the value of a desirable factor).

With this regard we will follow the indirect approach assuming the weak disposal technology.

Therefore, the following problem is obtained:

$$\max \ \beta_o$$

$$\text{s.t.} \ \sum_{j=1}^{n} \lambda_j y_{rj}^g \geq y_{ro}^g + \beta_o g_{yr}^g, r \epsilon GO,$$

$$\sum_{j=1}^{n} \lambda_j y_{rj}^b \leq y_{ro}^b - \beta_o g_{yr}^b, r \epsilon BO,$$

$$\sum_{j=1}^{n} \lambda_j x_{ij}^g \leq x_{io}^g - \beta_o g_{xi}^g, i \epsilon GI,$$

$$\sum_{j=1}^{n} \lambda_j = 1, \lambda_j \geq 0 \ (\forall_j), \qquad (8)$$

where all *GO/GI* and *BO* are the indexes that designate the presence of good outputs/inputs and bad outputs; 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 with regard to 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 (8) is obtained by solving the following LP problem, considering that β_o^*, is obtained in the optimal solution to (9):

$$\max \sum_{r \ \epsilon \ CGO} s_r^+ + \sum_{r \ \epsilon \ CBO} s_r^- + \sum_{i \ \epsilon \ CGI} s_i^-,$$

$$\text{s.t.} \ \sum_{j=1}^{n} \lambda_j y_{rj}^g - s_r^+ = y_{ro}^g + \beta_o^* g_{yr}^g, r \epsilon GO,$$

$$\sum_{j=1}^{n} \lambda_j y_{rj}^b + s_r^- = y_{ro}^b - \beta_o^* g_{yr}^b, r \epsilon BO,$$

$$\sum_{j=1}^{n} \lambda_j x_{ij}^g + s_i^- = x_{io}^g - \beta_o^* g_{xi}^g, i \epsilon GI,$$

$$\sum_{j=1}^{n} \lambda_j = 1, \lambda_j \geq 0 \ (\forall_j),$$

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

$$s_i^- \geq 0 \ (\forall_{i \epsilon \ GI}), \qquad (9)$$

Let (β_o^*, s_r^{+*}, s_r^{-*}, s_i^{-*}, λ_j^*) be the optimal solution to (9). Consider the reference set of the DDF-inefficient DMU$_o$ as follows:

$$\text{E}_o = \{ \text{j}: \lambda_j^* > 0, \text{j}=1, \ldots, \text{n}\}. \qquad (10)$$

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

$$(\widehat{\boldsymbol{x}}_o, \widehat{\boldsymbol{y}}_o) = (\textstyle\sum_{j\epsilon\ \ o} \lambda_j^* \boldsymbol{x}_j^g, \sum_{j\epsilon E_o} \lambda_j^* \boldsymbol{y}_j^g, \sum_{j\epsilon E_o} \lambda_j^* \boldsymbol{y}_j^b). \qquad (11)$$

2.3. The selection of inputs and outputs

One of DEA's drawbacks is that it does not provide a means to select the inputs and outputs that should be considered in the assessment of each DMU. However, the efficiency score attained for each DMU is highly dependent on this selection procedure (Nataraja and Johnson, 2011). In this case, if the number of inputs and outputs is considerably big, the dimensionality of the production space will increase and proportionally the discriminatory power of DEA will decrease. Hence, 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 particular inputs and outputs is not prolific, there are several approaches that 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 and in our assessment, we have started our analysis by considering the contributions of previous research, in particular the studies conducted in Luptacik and Bohm (2006), Luptacik and Mahlberg (2013), Lábaj et al. (2014) and Zurano-Cervelló et al. (2018) (see Table 2).

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 approaches used, it was possible to prove that the DEA models used did not satisfy our requirement of using a radial and non-oriented model. Therefore, we have selected the DDF model for this study. The choice of the 28 EU countries came through combining the studies of Lábaj et al. (2014) and Zurano-Cervelló et al. (2018), 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 3.

Table 2. 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

Table 3. 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 missions	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 €

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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) – see Figures 1A to 3A (Appendix 1). 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) – see Figures 4A to 6A (Appendix 1). Tables 4 and 5 provide information on the descriptive statistics regarding the inputs and outputs considered in 2010 and 2014, respectively.

Table 4. Descriptive statistics of all DMUs in 2010 – direct production chain

	Labour (X1000)	***K (x10^6 €)***	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***
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

Source: Authors' own calculations.

Table 5. Descriptive statistics of all DMUs in 2014 – direct production chain

	Labour (X1000)	***K (x10^6 €)***	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***
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

Source: Authors' own calculations.

From the observation of Tables 4 and 5 it can be concluded that there has been a decrease of the average environmental emissions from 2010 to 2014 in the direct production chain of the electricity sector, although the average capital stock and the GVA in this sector is 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 horizon (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) – see Figures 7A and 8A of Appendix 2 (direct consumption supply chain) and Figures 12A and 13A of Appendix 3 (indirect consumption supply chain). 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) – see Figures 9A to 11A of Appendix 2 (direct consumption supply chain) and Figures 14A and 16A of Appendix 3 (indirect consumption supply chain). Tables 6 to 9 provide information on the descriptive statistics regarding the inputs and outputs considered in the direct and indirect consumption supply chain 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 in order to avoid double counting, since this sector is already incorporated in final demand. From the analysis of Tables 6 to 9 it might be concluded 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 in the indirect consumption supply chain which have alone an amount of emissions and GVA bigger than the rest of the sectors of both chains combined, since all the sectors directly engaged to the electricity sector are dependent of the electricity sector itself for its 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 5 sectors that contribute most to emissions in the electricity sector, both in 2010 and 2014, are: the electricity sector itself (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. In spite of that fact, if we isolate ACG or O3PR emissions, sector E37-E39 is replaced by sector A01 - Crop and animal production, hunting and related service activities in the top five contributors – see Figures 37A to 42A (Appendix 7).

Finally, the indirect consumption supply chain follows a similar trend. In this last case, the top five sectors that contribute most to pollutant emissions in the electricity sector, both in 2010 and 2014, are the same obtained in the direct consumption supply chain with the exception of 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 – see Figures 47A to 52A (Appendix 8).

Table 6. Descriptive statistics of all DMUs in 2010 – direct consumption supply chain

	Labour (X1000)	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***
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

Source: Authors' own calculations.

Table 7. Descriptive statistics of all DMUs in 2014 – direct consumption supply chain

	Labour (X1000)	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***
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

Source: Authors' own calculations.

[1] The identification of all direct/indirect sectors of consumption supply chain, mentioned as responsible for the changes of inputs and output of electricity sector throughout this work, is presented in Table 1A in appendix 9.

Table 8. Descriptive statistics of all DMUs in 2010 – indirect consumption supply chain

	Labour (X1000)	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***
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

Source: Authors' own calculations.

Table 9. Descriptive statistics of all DMUs in 2014 – indirect consumption supply chain

	Labour (X1000)	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***
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

Source: Authors' own calculations.

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4. Discussion of some illustrative results

4.1. Production chain

The study involved applying models (7) to (9) to the 28 DMUs under evaluation. Tables 14 and 15 (direct production chain), tables 20 and 21 (direct consumption supply chain) and tables 26 and 27 (indirect consumption supply chain) depict the overall efficiency scores $(1 - \beta_o)$ (obtained with the super-efficiency model) for the periods of 2010 and 2014, respectively, according to each DEA model considered. Tables 10 to 13 present information on the descriptive statistics of both efficient and non-efficient DMUs in the case of the eco-efficiency assessment of the direct production chain of the electricity sector. From the analysis of these tables it might be concluded that the average super efficiency 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 downwards 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 a 40% an increase 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).

Table 10. Descriptive statistics of efficient DMUs in 2010 – direct production chain

	Labour (X1000)	***K (x10^6 €)***	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***	***Super efficiency score***
Minimum	1	404	1,206	1	3	70	1.01
Maximum	249	219,861	357,283	435	423	56,033	6.55
Average	62	61,572	55,679	105	84	13,264	1.87
Standard deviation	75	75,184	100,860	146	121	16,916	1.70

Source: Authors' own calculations.

Table 11. Descriptive statistics of efficient DMUs in 2014 – direct production chain

	Labour (X1000)	*K (x10^6 €)*	*GHG (x1000 ton)*	*ACG (x1000 ton)*	*O3PR (x1000 ton)*	*GVA (x10^6 €)*	*Super efficiency score*
Minimum	1	550	765	1	2	43	1.06
Maximum	250	222,906	352,117	424	407	49,571	5.92
Average	62	67,289	53,437	99	78	13,205	1.80
Standard deviation	75	78,070	97,764	128	116	15,763	1.52

Source: Authors' own calculations.

Table 12. Descriptive statistics of inefficient DMUs in 2010 – direct production chain

	Labour (X1000)	*K (x10^6 €)*	*GHG (x1000 ton)*	*ACG (x1000 ton)*	*O3PR (x1000 ton)*	*GVA (x10^6 €)*	*Efficiency score*
Minimum	8	2,947	4,020	9	7	502	0.61
Maximum	178	80,800	168,752	652	359	18,103	0.98
Average	36	22,074	41,192	134	81	4,240	0.86
Standard deviation	48	20,812	52,057	184	115	4,631	0.11

Source: Authors' own calculations.

Table 13. Descriptive statistics of inefficient DMUs in 2014 – direct production chain

	Labour (X1000)	*K (x10^6 €)*	*GHG (x1000 ton)*	*ACG (x1000 ton)*	*O3PR (x1000 ton)*	*GVA (x10^6 €)*	*Efficiency score*
Minimum	2	2,136	1,908	4	6	299	0.56
Maximum	157	125,741	158,127	497	312	30,039	0.99
Average	33	27,397	32,169	78	61	4,853	0.84
Standard deviation	46	30,973	46,896	133	98	7,400	0.13

Source: Authors' own calculations.

In 2010, Table 14 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 are 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 are Ireland and France followed by Malta and Luxemburg (these last two *ex aequo*) – see Table 15.

Table 14. Data and efficiency scores obtained in the direct production chain in 2010

	Inputs					*Outputs*			
DMU	***Labour (X1000)***	***K (x10^6 €)***	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***	***Inefficiency Score***	***Super-Efficiency Score***	***Nº of times as Ref.***
Luxemburg	1	2,882	1,377	1	3	306	-5.55	6.55	6
Malta	2	404	1,206	11	6	70	-3.10	4.10	10
Germany	249	179,671	357,283	435	423	56,033	-0.54	1.54	9
Sweden	28	60,385	10,768	18	24	9,577	-0.28	1.28	3
Spain	60	108,386	60,192	153	152	25,533	-0.22	1.22	4
Italy	85	219,861	117,850	86	122	25,238	-0.22	1.22	0
Romania	124	10,314	37,877	350	80	4,581	-0.16	1.16	6
France	133	101,256	41,711	156	139	25,525	-0.15	1.15	1
Belgium	19	23,578	22,317	14	24	6,178	-0.14	1.14	9
Austria	27	26,804	11,205	11	15	5,222	-0.04	1.04	0
Cyprus	2	1,656	3,884	25	8	291	-0.03	1.03	2
Latvia	12	3,672	2,483	4	8	618	-0.01	1.01	0
Lithuania	14	3,880	4,020	9	7	811	0.02	0.98	0
Portugal	9	15,977	12,020	30	22	3,343	0.03	0.97	0
Bulgaria	32	3,123	34,188	376	62	1,184	0.03	0.97	0
Croatia	19	3,553	5,055	15	10	852	0.05	0.95	0
Netherlands	24	38,221	52,108	23	31	7,301	0.06	0.94	0
Denmark	11	31,127	21,505	16	26	3,643	0.06	0.94	0
Finland	13	20,742	28,047	63	58	4,208	0.07	0.93	0
Ireland	12	11,565	12,932	18	16	2,492	0.10	0.90	0
Greece	20	11,883	48,487	245	148	2,909	0.12	0.88	0
Poland	178	42,094	168,752	652	359	11,084	0.13	0.87	0
Czech Republic	32	26,825	57,813	165	113	5,775	0.15	0.85	0
United Kingdom	129	80,800	165,796	351	357	18,103	0.17	0.83	0
Hungary	39	14,202	17,098	27	33	2,312	0.25	0.75	0
Estonia	9	2,947	14,655	88	19	502	0.27	0.73	0
Slovenia	8	6,300	6,469	14	14	835	0.28	0.72	0
Slovakia	20	39,948	10,122	61	17	2,487	0.39	0.61	0

Source: Authors' own calculations.

Table 15. Data and efficiency scores obtained in the direct production chain in 2014

	Inputs					*Outputs*			
DMU	***Labour (X1000)***	***K (x10^6 €)***	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***	***Inefficiency Score***	***Super-Efficiency Score***	***Nº of times as Ref.***
Luxemburg	1	3,772	765	1	2	198	-4.92	5.92	7
Malta	1	550	1,077	7	3	43	-2.88	3.88	7
Germany	250	183,877	352,117	424	407	49,571	-0.33	1.33	1
Sweden	29	73,651	6,778	12	18	9,185	-0.21	1.21	3
Spain	59	127,562	63,069	224	186	22,277	-0.15	1.15	3
Italy	87	222,906	90,926	54	86	24,713	-0.06	1.06	0
Romania	107	12,902	33,428	173	64	4,982	-0.13	1.13	5
France	140	121,679	23,826	76	69	33,005	-0.52	1.52	8
Belgium	19	26,949	16,144	8	15	6,008	-0.15	1.15	4
Austria	27	30,490	6,873	8	12	4,937	0.01	0.99	0
Cyprus	2	2,136	2,953	20	9	299	0.15	0.85	0
Latvia	12	4,863	1,908	4	8	639	0.05	0.95	0
Lithuania	11	4,926	2,168	7	6	796	0.10	0.90	0
Portugal	8	16,860	12,180	28	26	3,400	-0.08	1.08	2
Bulgaria	27	3,633	30,234	165	48	1,442	-0.06	1.06	2
Croatia	14	5,251	3,774	8	8	936	0.13	0.87	0
Netherlands	24	51,804	48,741	20	23	7,264	0.04	0.96	0
Denmark	10	31,852	12,533	10	16	3,010	0.08	0.92	0
Finland	14	24,935	16,853	40	41	3,971	0.15	0.85	0
Ireland	10	13,124	10,701	11	11	3,639	-0.10	1.10	13
Greece	18	12,399	40,591	121	113	2,815	0.12	0.88	0
Poland	157	47,840	158,127	497	287	12,077	0.08	0.92	0
Czech Republic	33	27,598	49,227	124	81	5,395	0.17	0.83	0
United Kingdom	139	125,741	130,868	278	312	30,039	0.05	0.95	0
Hungary	31	13,086	12,434	21	22	1,788	0.34	0.66	0
Estonia	8	5,191	13,414	41	13	624	0.37	0.63	0
Slovenia	9	7,877	4,527	10	8	916	0.31	0.69	0
Slovakia	18	42,364	9,717	37	14	2,139	0.44	0.56	0

Source: Authors' own calculations.

The countries with the lowest eco-efficiency performance both in 2010 and in 2014 are Hungary, Estonia, Slovenia and Slovakia – Tables 14 and 15.

In 2014, Austria, Cyprus and Latvia lose their efficiency status while Ireland, Portugal and Bulgaria become efficient – see Figure 2.

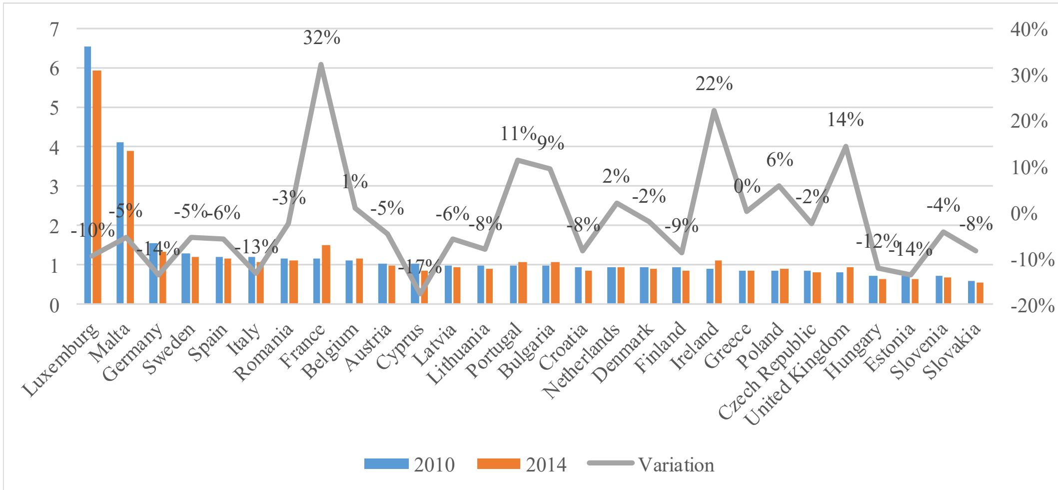

Figure 2. Super efficiency scores in 2010 and 2014 - Direct Production Chain

Through the analysis of the super efficiency scores attained (Figure 2), we can establish some important facts. When analysing the period as a whole, we can point out that except from the countries that have become efficient, only Poland, 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 super efficiency 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 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 who 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 expands GVA and capital stock by 2% and 6%, respectively, and labour drops by 11%), Ireland (which increases GVA and capital stock by 46% and 13%, respectively, and labour decreases by 17%) and Bulgaria (which boosts GVA and capital stock by 22% and 16%, respectively, and labour declines 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 fuels generation and the increased production of renewable energy (according to 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) – see Figure 3.

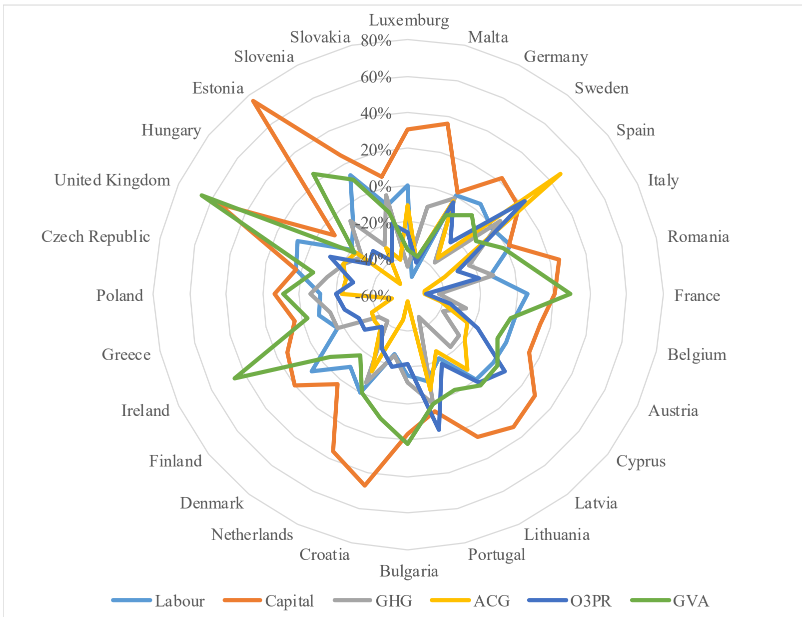

Figure 3. Changes of inputs and outputs between 2010 and 2014 – Direct Production Chain

Regarding France, a similar conclusion is reached, in spite of the increase of labour in 5%, since there has been an increase of the GVA and capital stock of 29% and 20%, respectively, while electricity generation from renewable has increased by 18% and fossil fuel electricity generation had a cut of 51% during this period of analysis (European Commission, 2018). The improvement of the efficiency of Belgium is mainly explained by the renewable electricity generation increase by 70% and a fuel generation decrease by 37% (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 which have to reduce labour by 35%; 77%, 64%; 73%, 70%, 38%, 51% and 44%, respectively) and capital (Denmark, Hungary, Estonia, Slovenia and Slovakia, which require a reduction of the capital stock of 61%, 34%, 38%, 31% and 44%), whereas GHG emissions can also become a critical factor in terms of eco-efficiency (Czech Republic, Slovakia, Estonia, Greece, Hungary, Cyprus and Slovenia need to reduce their GHG emissions by 73%, 62%, 62%, 61%, 37%, 33% and 31%, respectively) namely due to an increase of electricity generation from solid fuels and Petroleum products in Netherlands (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 (See Figures 21A and 22A of the Appendix 4).

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 17A to 22A (Appendix 4).

An interesting fact comes out regarding the loss of efficiency of Cyprus, Latvia and Austria. These countries kept the labour unchanged and decreased GHG and ACG emissions. However, Cyprus enlarged its capital stock and GVA in 29% and 3% and Latvia augmented capital stock and GVA in 32% and 3%, respectively, while Austria increased capital stock but decreased GVA. It is interesting to mention as well, that in this time horizon, Cyprus and Austria amplified slightly their installed capacity of fossil fuel power plants and considerably the installed capacity of renewable electricity whereas Latvia had an opposite behaviour but cut the electricity generation from renewable sources by 23% (European Commission, 2018).

4.2. Consumption chain

4.2.1. Direct consumption supply chain

Tables 16 to 19 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 analysis of these tables it might be concluded that the average superefficiency values have increased from 2010 to 2014, mainly due to Cyprus, that increased its super efficiency from 3.74 to 15.87, 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 labour.

Table 16. Descriptive statistics of efficient DMUs in 2010 – direct consumption supply chain

	Labour (X1000)	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***	***Super efficiency score***
Minimum	0	110	0	0	31	1.05
Maximum	150	23,958	47	60	11,077	3.74
Average	34	7,057	13	15	3,331	1.56
Standard deviation	47	9,474	17	20	3,693	0.84

Source: Authors' own calculations.

Table 17. Descriptive statistics of efficient DMUs in 2014 – direct consumption supply chain

	Labour (X1000)	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***	***Super efficiency score***
Minimum	0	5	0	0	16	1.01
Maximum	148	21,975	37	54	11,285	15.87
Average	27	4,492	8	10	2,897	2.73
Standard deviation	46	8,051	14	18	4,029	4.62

Source: Authors' own calculations.

Table 18. Descriptive statistics of inefficient DMUs in 2010 – direct consumption supply chain

	Labour (X1000)	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***	***Efficiency score***
Minimum	1	137	0	1	18	0.27
Maximum	58	5,008	19	13	3,171	0.97
Average	13	1,586	5	4	616	0.61
Standard deviation	14	1,550	6	4	733	0.22

Source: Authors' own calculations.

Table 19. Descriptive statistics of inefficient DMUs in 2014 – direct consumption supply chain

	Labour (X1000)	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***	***Efficiency score***
Minimum	2	159	0	1	124	0.26
Maximum	55	7,861	19	17	4,150	0.93
Average	15	1,955	5	4	876	0.57
Standard deviation	15	2,216	5	5	1,129	0.21

Source: Authors' own calculations.

In 2010, Table 20 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) are Luxembourg, Denmark and Sweden (these last two *ex aequo*). In 2014, Table 21 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 are Denmark followed by Cyprus and Sweden (these last two *ex aequo*).

Table 20. Data and efficiency scores obtained in the direct consumption supply chain in 2010

	Inputs				***Outputs***			
DMU	***Labour (X1000)***	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***	***Inefficiency Score***	***Super-Efficiency Score***	***Nº of times as Ref.***
Cyprus	1	140	0	0	31	-2.740	3.740	0
Luxemburg	0	110	0	0	46	-0.686	1.686	15
Germany	150	23,958	31	33	11,077	-0.455	1.455	2
Denmark	5	1,132	2	3	1,213	-0.291	1.291	13
Sweden	10	421	1	1	991	-0.274	1.274	13
Belgium	16	873	1	1	1,252	-0.219	1.219	3
France	48	5,873	22	20	5,317	-0.216	1.216	3
United Kingdom	44	21,621	47	60	6,337	-0.140	1.140	1
Italy	33	9,387	10	14	3,719	-0.049	1.049	1
Austria	8	1,426	1	2	1,008	0.035	0.966	0
Netherlands	10	2,088	1	2	946	0.070	0.930	0
Spain	33	4,707	13	13	3,171	0.091	0.909	0
Malta	1	137	1	1	18	0.162	0.838	0
Finland	4	281	1	1	273	0.176	0.824	0
Ireland	2	704	1	1	215	0.181	0.819	0
Portugal	6	1,372	4	3	549	0.361	0.639	0
Poland	58	3,463	10	9	1,537	0.402	0.598	0
Slovakia	10	1,404	8	3	529	0.411	0.589	0
Slovenia	5	304	1	1	177	0.416	0.585	0
Croatia	5	409	2	1	212	0.429	0.571	0
Latvia	4	269	0	1	119	0.437	0.563	0
Lithuania	5	494	1	1	164	0.522	0.478	0
Hungary	15	680	1	2	389	0.525	0.475	0
Greece	10	3,843	19	12	595	0.584	0.416	0
Czech Rep	19	5,008	13	11	923	0.593	0.407	0
Estonia	3	843	5	1	104	0.612	0.388	0
Bulgaria	13	708	7	2	195	0.711	0.289	0
Romania	32	1,987	13	6	569	0.729	0.271	0

Source: Authors' own calculations.

Table 21. Data and efficiency scores obtained in the direct consumption supply chain in 2014

	Inputs				*Outputs*			
DMU	***Labour (X1000)***	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***	***Inefficiency Score***	***Super-Efficiency Score***	***Nº of times as Ref.***
Cyprus	1	5	0	0	18	-14.868	15.868	10
Luxemburg	1	78	0	0	53	-0.579	1.579	2
Germany	148	21,975	28	29	11,285	-0.352	1.352	0
Denmark	4	766	1	2	1,041	-0.230	1.230	15
Sweden	10	265	1	1	1,001	-0.263	1.263	10
Belgium	16	616	1	1	1,353	-0.258	1.258	6
France	44	3,344	10	10	5,886	-0.439	1.439	5
United Kingdom	47	17,014	37	54	8,000	-0.188	1.188	2
Italy	42	7,861	9	11	4,150	0.140	0.860	0
Austria	9	905	1	2	1,051	0.068	0.932	0
Netherlands	16	2,691	2	2	1,343	0.087	0.914	0
Spain	36	5,405	19	17	3,293	0.242	0.758	0
Malta	0	110	1	0	16	-0.140	1.140	0
Finland	3	159	0	1	254	0.144	0.856	0
Ireland	1	747	1	1	316	-0.014	1.014	2
Portugal	6	1,425	3	3	550	0.442	0.559	0
Poland	55	2,962	7	7	1,533	0.563	0.437	0
Slovakia	8	1,497	6	2	492	0.459	0.542	0
Slovenia	5	202	0	1	180	0.437	0.563	0
Croatia	4	318	1	1	198	0.421	0.579	0
Latvia	4	215	0	1	136	0.519	0.481	0
Lithuania	3	200	1	1	124	0.448	0.552	0
Hungary	13	398	1	1	307	0.596	0.405	0
Greece	8	3,691	11	10	539	0.583	0.417	0
Czech Rep	20	4,896	11	9	937	0.608	0.393	0
Estonia	2	649	2	1	125	0.482	0.518	0
Bulgaria	10	520	3	1	158	0.733	0.267	0
Romania	21	1,193	3	4	405	0.739	0.261	0

Source: Authors' own calculations.

The countries with the lowest eco-efficiency performance both in 2010 and in 2014 are Bulgaria, Czech Republic and Romania – Tables 20 and 21.

In 2014, Italy loses its efficiency status while Ireland and Malta become efficient – see Figure 4.

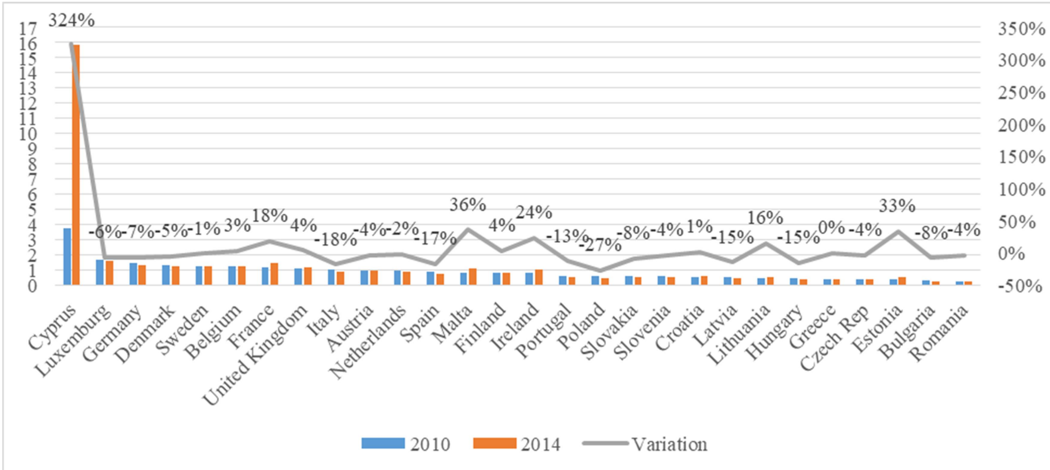

Figure 4. Super efficiency scores in 2010 and 2014 – Direct consumption supply chain

After analysing the super efficiency scores attained (Figure 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 help explain the evolution of the efficiency scores presented in Tables 20 and 21. 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. Despite the fact that Ireland has become more ecologic in electricity production, the increasing of GHG emissions might be related to the intensification of the intra-sector consumption (140%) in this period, which almost doubled the GVA growth. The remaining top 5 sectors with the highest environmental impacts on the electricity sector are A01, which increased from 2010 to 2014, B, C23 and H51 - Air transport, which reduced their impacts on the electricity sector– see Figures 33A to 42A (Appendix 7). Regarding the contribution to GVA and labour the most representative sector is also sector D35. In the case of Malta, this country had a significant reduction of emissions and a mild reduction of labour at the expense of decreasing its economic performance – see Figure 5 – as a result of the performance in sector D35. The remaining top 5 sectors with the highest contribution to pollutant emissions are H50, E37-

E39, which have decreased and H49 which stayed the same and H51, which have increased from 2010 to 2014.

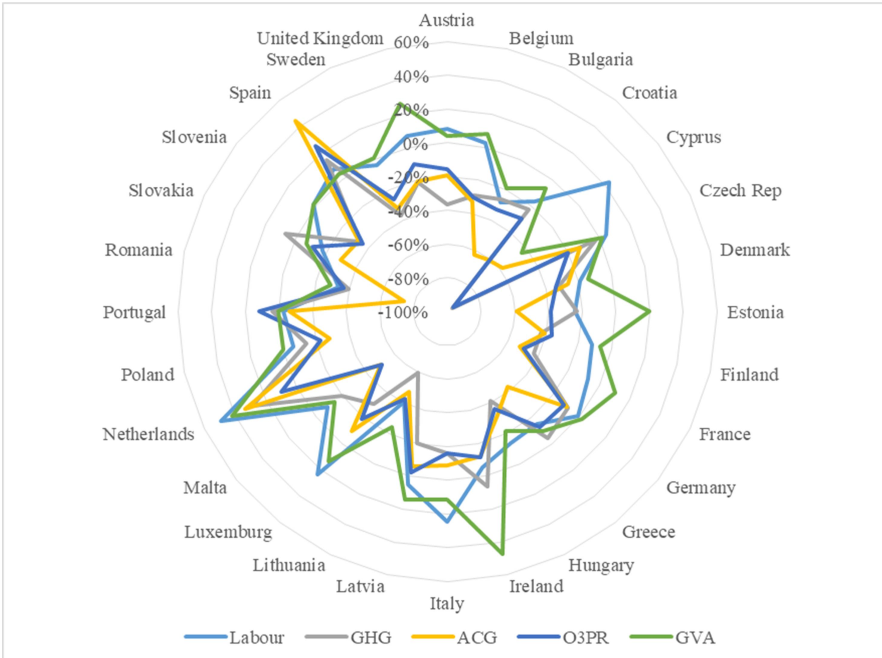

Figure 5. Changes of inputs and outputs between 2010 and 2014 – Direct consumption supply chain

Regarding the other countries that increased their efficiency they can be divided in two different groups: 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. The sector responsible for the improvement of the environmental performance of Belgium, France and the United Kingdom is sector D35, which is also the most representative sector for the economic performance of France and the United Kingdom, while sectors M69-M70 - Legal and accounting activities; activities of head offices; management consultancy activities are the main responsible for increasing the GVA of Belgium. The remaining top 5 representative sectors in terms of the environmental impacts are H49, E37-E39, F - Construction and N - Administrative and support service activities for the Belgium electricity sector; sectors C20 - Manufacture of chemicals and chemical products, E37-E39, H49 and C23 for the French electricity sector; and sectors B, C19, F and G46 - Wholesale trade, except of motor vehicles and motorcycles for the United Kingdom electricity sector. From 2010 to

2014 the environmental impacts of the sectors described above behave in the following manner: in Belgium, the emissions from sector H49 increase while those from sector E37-E39 decline and from sectors F and N remain equal; in France, the emissions from all sectors reduce; and, in the United Kingdom, the emissions from sectors B, C19 and G46 decrease while those from sector F remain equal.

On the other hand, in Cyprus, the most important sector in terms of environmental and economic performance is sector E37-E39, because it reduced almost the totality of its emissions. This behaviour is possibly explained by the electricity sold by producers to the grid at subsidised prices between 2008 and 2014. Between 2008 and 2010 the electricity generated from biogas sold at subsidised prices had a steep increase, since the Feed-in tariffs (FiT) paid to these renewable energy producers were higher than those payed to solar and wind energy producers. As of 2011 the prices of FiT payed to biogas electricity producers decreased while the prices payed to the other renewable energy producers grew significantly and became much more appealing (Mesimeris et al., 2019). In addition, between 2007 and 2010 the installed capacity of biogas increased from 1 to 8 MW and then only increased 2MW until 2014 (European Commission, 2018). The other top 5 sectors with a significant impact on emissions are C23 whose emissions remained equal from 2010 to 2014 while the environmental impacts from D35 and H49 decreased and from C19 augmented in the same period.

The second group of countries, such as Croatia, Estonia Finland, Greece and Lithuania experienced a strong reduction on 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. Croatia, however, split the importance of its environmental performance enhancement by the sectors D35, C19 and B, which represent almost all the emissions assigned to the electricity sector, sustaining the fact that the mineral industry has been an important component of Croatia's economy (Hastorun, 2016). The remaining top 5 sectors with a significant impact on emissions in Croatia are sectors E37-E39 and G46; in Estonia, sectors B, C19, C23 and G46; in Finland, sectors B, C19, C20 and H49; in Greece, sectors B, C19, C23 and A01; and, in Lithuania, sectors C19, E37-E39, C23 and H49.

Furthermore, from 2010 to 2014, the emission contributions to the electricity sector in Croatia increased in sectors E37-E39 and decreased in sector G46; in Estonia, increased in sector C19 while remaining equal in sectors B, C23 and G46; in Finland, enlarged in sector C20 while decreasing in sectors B, C19 and H49; in Greece, increased in sectors B and C23 whereas in sectors C19 and A01 declined; and, in Lithuania, the impacts for the electricity sector decreased in sectors C19, E37-E39 and C23, while those from sector H49 remained equal.

Regarding labour, the main responsible for its reduction are in Croatia, sectors G46, B and D35; in Estonia, sectors B; in Finland, sector F; in Greece, most of the sectors; and, in Lithuania, sectors D35, F and C33. In what concerns the GVA, Croatia (most representative sectors: G46 and B), Finland (most representative sectors: D35, B and C33), Greece (most representative sectors: G46 and K64 - Financial service activities, except insurance and pension funding) and Lithuania (most representative sectors: D35 and F) experienced a retraction while Estonia increased GVA due to sectors B, D35 and G46 – see Figures 33A to 42A (Appendix 7).

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 which have to reduce labour by 74%, 73%, 61%, 60% and 59%, respectively), the environmental performance by reducing GHG emissions (Greece, Estonia, Bulgaria, Czech Republic and Romania need to reduce their GHG emissions by 79%, 77%, 76%, 75% and 74%, respectively), reducing ACG emissions (Bulgaria, Greece, Estonia, Slovakia and Romania need to reduce their ACG emissions by 90%, 88%, 87%, 85% and 81%, respectively) and reducing O3PR emissions (Greece, Romania, Bulgaria, Latvia and Czech Republic need to reduce their O3PR emissions by 83%, 76%, 73%. 69% and 61% respectively).

Finally, in order to increase the economic performance Romania, Bulgaria, Czech Republic, Hungary and Greece need to increase their GVA by 74%, 73%, 61%, 60% and 58%, respectively.

Still concerning the countries with lower eco-efficiency in 2014, it is interesting to highlight the worsening of Italy, Spain, Netherlands, Romania, Bulgaria and Czech Republic. Italy became inefficient in 2014 mainly because of the growth of GVA, mainly due to sector H49, at the expense of a strong growth of labour in the majority of the sectors directly linked to electricity sector. Regarding pollutant emissions, the main contributor is sector D35 which reduced its emissions in 2014, followed by sectors E37-E39 (decreased emissions), H49 (increased emissions), C19 (decreased emissions) and A01 (strongly increased emission).

Spain increased significantly its emissions mainly due to sector D35 which increased its GHG emissions in 2014 because of the growth in the utilization of solid fuels by 73%. The remaining top 5 sectors in terms of their contribution to emissions in this country are C19 and H49, which have also increased their emission from 2010 to 2014, and C23 and C20 which have decreased their emissions in the same period. Netherlands followed a similar trend, increasing the usage of solid fuels for electricity generation by 31%. Nevertheless, in this latter case, while the GVA of the country as whole decreased, the GVA of sector D35 increased (European Commission, 2018). The remaining top 5 sectors with a significant environmental contribution in this country are A01, C19, F and H51 which have all increased from 2010 to 2014 - see Figures 33A to 42A (Appendix 7). Finally, Romania, Bulgaria and Czech Republic require the biggest adjustments in all inputs and outputs in order 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 23A to 27A (Appendix 5).

4.2.2. Indirect consumption supply chain

Tables 22 to 25 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 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.

Table 22. Descriptive statistics of efficient DMUs in 2010 – indirect consumption supply chain

	Labour (X1000)	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***	***Super efficiency score***
Minimum	1	439	1	1	36	1.07
Maximum	215	144,848	179	176	29,249	5.77
Average	62	29,196	41	42	8,724	1.91
Standard deviation	78	52,214	65	63	10,411	1.71

Source: Authors' own calculations.

Table 23. Descriptive statistics of efficient DMUs in 2014 – indirect consumption supply chain

	Labour (X1000)	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***	***Super efficiency score***
Minimum	1	338	0	1	105	1.01
Maximum	213	152,050	185	179	27,997	4.70
Average	54	26,350	34	34	8,384	1.71
Standard deviation	77	55,574	67	65	10,160	1.33

Source: Authors' own calculations.

Table 24. Descriptive statistics of inefficient DMUs in 2010 – indirect consumption supply chain

	Labour (X1000)	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***	***Efficiency score***
Minimum	1	893	2	3	170	0.19
Maximum	112	66,440	232	155	12,257	1.00
Average	27	14,713	49	30	2,468	0.66
Standard deviation	31	17,739	63	42	3,038	0.25

Source: Authors' own calculations.

Table 25. Descriptive statistics of inefficient DMUs in 2014 – indirect consumption supply chain

	Labour (X1000)	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***	***Efficiency score***
Minimum	1	352	1	1	26	0.23
Maximum	121	57,333	180	136	17,628	0.98
Average	28	13,107	34	26	2,927	0.65
Standard deviation	33	15,921	45	36	4,343	0.23

Source: Authors' own calculations.

In 2010, Table 26 shows the existence of 7 efficient countries (Luxemburg, Germany, Malta, France, Sweden, Italy e Austria) from which the three countries more frequently nominated as benchmarks regarding the indirect consumption supply chain of the electricity sector are Sweden, Luxembourg and Austria. In 2014, Table 27 also presents 7 efficient countries (Luxemburg, Germany, France, Sweden, Austria, Belgium e Ireland) from which the top three countries mainly regarded as a reference in terms of best practices are Sweden, Luxembourg and Ireland.

Table 26. Data and efficiency scores obtained in the indirect consumption supply chain in 2010

	Inputs				*Outputs*			
DMU	***Labour (X1000)***	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***	***Inefficiency Score***	***Super-Efficiency Score***	***Nº of times as Ref.***
Luxemburg	1	576	1	1	140	-4.775	5.775	17
Germany	215	144,848	179	176	29,249	-0.516	1.516	3
Malta	1	439	4	2	36	-0.314	1.314	1
France	110	17,478	65	60	14,163	-0.313	1.313	2
Sweden	20	5,362	9	12	5,197	-0.276	1.276	21
Italy	70	31,482	27	37	9,644	-0.115	1.115	0
Austria	20	4,183	4	6	2,640	-0.069	1.069	7
Denmark	10	12,502	10	16	2,448	0.005	0.996	0
Belgium	23	15,263	10	17	4,943	0.048	0.952	0
Spain	60	15,634	42	43	8,563	0.054	0.946	0
Finland	6	7,391	17	15	1,270	0.077	0.923	0
Ireland	5	5,218	7	7	1,050	0.110	0.891	0
Netherlands	16	19,796	9	12	3,235	0.114	0.886	0
Latvia	9	893	2	3	304	0.142	0.858	0
United Kingdom	112	66,440	143	155	12,257	0.159	0.841	0
Cyprus	1	2,051	13	4	170	0.189	0.811	0
Portugal	13	4,097	10	8	1,474	0.349	0.651	0
Lithuania	10	1,853	4	4	437	0.369	0.631	0
Slovakia	20	4,445	26	8	1,385	0.383	0.617	0
Greece	16	24,051	122	74	1,754	0.392	0.608	0
Croatia	12	2,235	7	5	488	0.451	0.549	0
Czech Rep	32	25,890	74	51	3,064	0.452	0.548	0
Slovenia	7	3,343	7	7	519	0.536	0.464	0
Poland	103	60,198	232	130	4,862	0.600	0.400	0
Hungary	23	7,276	12	14	1,140	0.646	0.354	0
Estonia	6	6,608	40	9	271	0.652	0.348	0
Romania	61	10,442	94	23	1,628	0.698	0.303	0
Bulgaria	22	13,353	147	25	569	0.806	0.194	0

Source: Authors' own calculations.

Table 27. Data and efficiency scores obtained in the indirect consumption supply chain in 2014

	Inputs				Outputs			
DMU	***Labour (X1000)***	***GHG (x1000 ton)***	***ACG (x1000 ton)***	***O3PR (x1000 ton)***	***GVA (x10^6 €)***	***Inefficiency Score***	***Super-Efficiency Score***	***Nº of times as Ref.***
Luxemburg	1	338	0	1	105	-3.695	4.695	14
Germany	213	152,050	185	179	27,997	-0.370	1.370	1
Malta	1	352	2	1	26	0.016	0.984	0
France	100	10,058	32	30	16,323	-0.499	1.499	5
Sweden	21	3,535	6	10	5,211	-0.195	1.195	16
Italy	83	25,679	21	29	10,473	0.045	0.955	0
Austria	19	2,738	4	5	2,570	-0.006	1.006	5
Denmark	9	7,229	6	10	2,032	0.100	0.900	0
Belgium	23	11,535	6	11	5,017	-0.008	1.008	0
Spain	66	16,829	61	52	8,363	0.180	0.820	0
Finland	5	3,894	9	10	1,072	0.204	0.797	0
Ireland	4	4,193	4	4	1,464	-0.179	1.179	10
Netherlands	20	19,461	8	9	3,624	0.153	0.847	0
Latvia	9	702	1	3	337	0.249	0.751	0
United Kingdom	121	51,950	113	136	17,628	0.026	0.974	0
Cyprus	1	1,469	10	4	161	0.112	0.888	0
Portugal	13	4,194	10	9	1,503	0.389	0.611	0
Lithuania	7	1,070	3	3	433	0.376	0.624	0
Slovakia	17	4,800	18	7	1,310	0.434	0.566	0
Greece	14	19,333	58	54	1,593	0.433	0.567	0
Croatia	9	1,679	4	4	506	0.438	0.562	0
Czech Rep	34	24,340	61	40	3,130	0.465	0.535	0
Slovenia	8	2,518	5	5	590	0.507	0.493	0
Poland	91	57,333	180	106	5,254	0.542	0.458	0
Hungary	21	6,400	11	12	1,034	0.669	0.331	0
Estonia	5	6,363	20	7	346	0.626	0.374	0
Romania	39	7,781	40	15	1,398	0.685	0.315	0
Bulgaria	17	11,874	65	19	649	0.771	0.229	0

Source: Authors' own calculations.

The countries with the lowest eco-efficiency performance both in 2010 and in 2014 are Bulgaria, Estonia, Hungary and Romania – Tables 26 ad 27.

In 2014, Malta and Italy lose their efficiency status while Belgium and Ireland became efficient – see Figure 6.

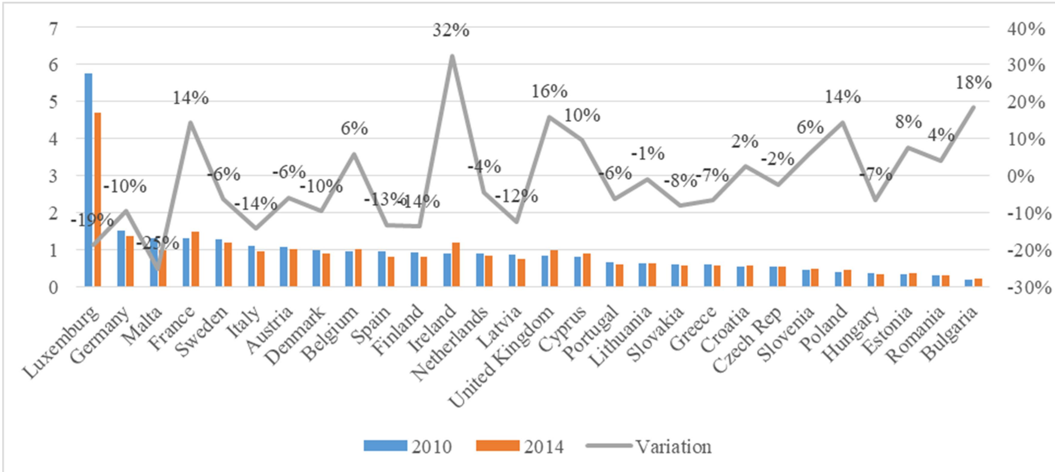

Figure 6. Super efficiency scores in 2010 and 2014 – Indirect consumption supply chain

Through the analysis of the super efficiency scores attained (Figure 6), we can conclude that except 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 26 and 27, since all the activity sectors are extremely dependent on this sector for the production of goods and services. This is highlighted in the difference between the sectors in the first (D35 for all countries) and second places in the thermic tables, regarding labour, emissions and GVA – see Figures 43A to 52A (Appendix 8). Due to this dependency the evolution of the 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 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 on 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 of 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 the economic performance and labour productivity are also the responsibility of sector D35. The remaining sectors which have a representative impact on indirect emissions for the electricity sector are, in Belgium, C23, H49, F and A01 and, in Ireland, C23, A01, H49 and B – see Figures 43A to 52A (Appendix 8). From 2010 to 2014 the emission contributions in Belgium increased in sector C23, remained the same in sector H49 and decreased in sectors F and A01, whereas in Ireland sector A01 increased its emissions while the emissions from the remaining sectors were kept the same.

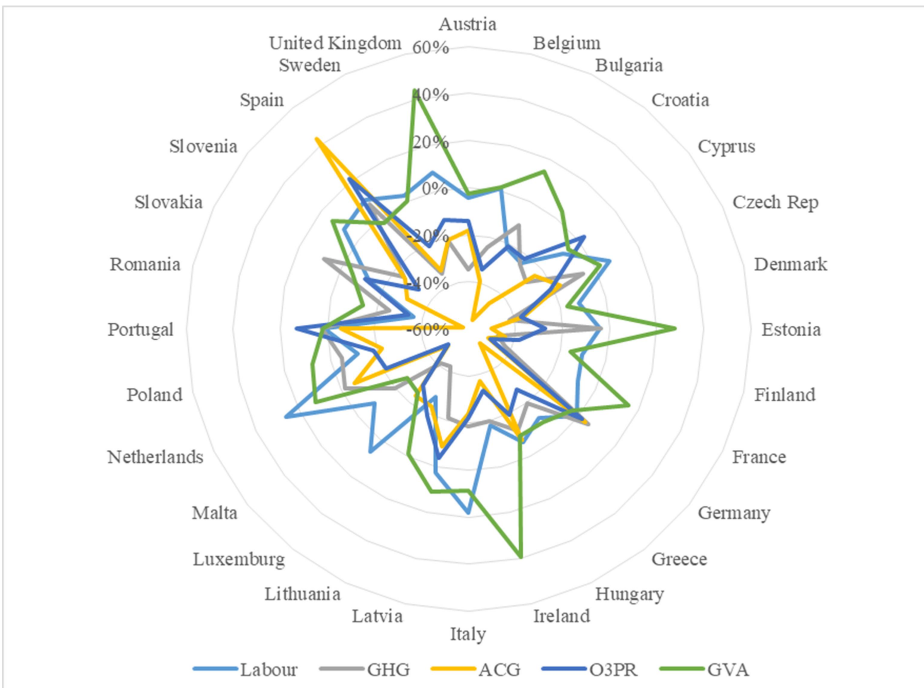

Figure 7. Changes of inputs and outputs between 2010 and 2014 – Indirect consumption supply chain

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%). 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 with the exception of sector D35, which had an increase in 2014. The remaining major contributors to the indirect emissions of the French electricity sector are sectors E37-E39, C20, C23 and H49 – see Figures 43A to 52A (Appendix 8). From 2010 to 2014 all those sectors decreased their emissions.

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). The remaining sectors with a significant impact on indirect emissions are, in Bulgaria, H49 (increased from 2010 - 2014), C23 (decreased from 2010 to 2014), A01 (reduced from 2010 to 2014) and F (remain equal from 2010 to 2014); in Croatia, B (decreased from 2010 to 2014), C19 (declined from 2010 to 2014), E37-E39 (remain equal from 2010 to 2014) and A01(increased from 2010 to 2014); in Cyprus, E37-E39 (declined from 2010 to 2014), C23 (reduced from 2010 to 2014), G46 (decreased from 2010 to 2014) and G47 - Retail trade, except of motor vehicles and motorcycles (augmented from 2010 to 2014); in Estonia, H49 (decreased from 2010 to 2014), C19 (declined from 2010 to 2014), B (reduced from 2010 to 2014) and C23 (remain equal from 2010 to 2014); in Poland, B (decreased from 2010 to 2014), C23 (reduced from 2010 to 2014), H49 (remain equal from 2010 to 2014) and C19 (declined from 2010 to 2014); in Romania, B (decreased from 2010 to 2014), C23 (decreased from 2010 to 2014), C24 - Manufacture of basic metals (reduced from 2010 to 2014) and H49 (remain equal from 2010 to 2014); in Slovenia, H49 (decreased from 2010 to 2014), B (reduced from 2010 to 2014), C23 (reduced from 2010 to 2014) and A01 (remain equal from 2010 to 2014); and, in the United Kingdom, B (decreased from 2010 to 2014), H49 (increased from 2010 to 2014), C23 (enlarged from 2010 to 2014) and H51 (decreased from 2010 to 2014) – see Figures 43A to 52A (Appendix 8). Regarding the economic performance, Bulgaria, Croatia, Estonia, Poland, Slovenia and in the United Kingdom increased their GVA, while Cyprus and Romania had the opposite trend, as a result of the behaviour of sector D35 in the indirect consumption supply chain - see Figures 43A to 52A (Appendix 8).

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, Cyprus should reduce their O3PR emissions by 90%, 86%, 82%. 78% and 73% respectively).

Finally, in order 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 also decreased its GVA by 27%, in which sector D35 had the most important role. The top 5 sectors with the highest impact on indirect emissions for the electricity sector are, in Italy, D35, E37-E39, H49, C19 and A01 and, in Malta, D35, H50, E37-E39, H49 and H51 – see Figures 43A to 52A (Appendix 8). From 2010 to 2014, the environmental impacts from the indirect consumption supply chain sectors had the following behaviour: in Italy, decreased in sectors D35, E37-E39 and C19 and increased in sectors H49 and A01, and, in Malta, the reduced in sectors D35, and H50, remained unchanged in sectors E37-E39 and H49, and augmented in sector H51. 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 in 2%. The loss of environmental performance is linked to sector D35 which augmented its emissions contributions due to the use of solid fuels for electricity generation, as already mentioned (European Commission, 2018). The loss of labour productivity and economic performance are specially related to the increase of labour in sector N and with 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 (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 due to the fact that 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 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 Emissions 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 reduce 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 FiT to premium market and direct market policies; growth corridors for renewables in which the feed-in remuneration is adjusted to the amount of new installations and the national target of installed capacity; set 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 5 countries that require adjustment in all of its inputs and outputs.

The overall adjustments prescribed by the DDF model regarding the direct consumption supply chain of the electricity sector are provided in Figures 28A to 32A (Appendix 6).

4.2.3. Variations in terms of contributions of emissions for the electricity sector

In order to understand how the electricity sector is influenced in terms of environmental impacts, it is necessary to understand 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 28 it is possible to observe that the sectors with the biggest direct contribution to the increase of emissions in the electricity sector are A01, H51, 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 with the exception of sectors H49 and H52. It's 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 29, it can be noted that the sectors with the highest direct impact on the reduction of emissions in the electricity sector are sectors D35, B, E37-E39, C19 and C20. Additionally, the countries that significantly reduce the emission contributions of the electricity sector are 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). In addition, France remains as one of the biggest reducers in emissions in the remaining sectors of Table 29 due to its electricity production structure, based on "clean energy" (77% Nuclear; 18% Renewables) and 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 shares 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 later plays a major role in the production of coal (Brown et al., 2016).

Another interesting fact regarding Germany is the 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 manufacture of the components of wind turbines in which Germany is the largest producer of the European Union (EU-MERCI, 2012). These findings can possibly be related to the fact that Germany is the biggest player of EU28, since it is the country with the largest wind power installed capacity and with the higher amount of electricity generated from this renewable source (European Commission, 2018).

The emissions produced by sector E37-E39 are led by Italy, which reduced in 2014, and are related to the 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 chemicals industry, representing the second-largest producer in Europe and the sixth in the world, respectively (Le Vély, 2015).

Table 28. TOP 5 increasing sectors - direct consumption supply chain

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

Source: Authors' own calculations

Table 29. TOP 5 decreasing sectors - direct consumption supply chain

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

Source: Authors' own calculations

Regarding Table 30, it can be pointed out that the sectors which mostly contribute indirectly for increasing the emissions of the electricity sector are A01, H51, A03, C26 - Manufacture of computer, electronic and optical products and U - Activities of extraterritorial organizations and bodies. In this case, Italy has the biggest increase of emissions in sectors A01 (same justification of direct consumption supply chain) and H51, while Slovakia occupies the first place in sector A03.

After analysing the results of Table 31 it is possible to note that the sectors that highly contribute indirectly to the reduction of emissions in the electricity sector are D35, B, C23, E37-E39 and C20. In this situation, France presents the highest emission reduction in all sectors. The other countries with the biggest declines in terms of emissions of the sectors presented in Table 31 are Italy, in sector C23; Spain, in sector B; the United Kingdom in sector D35; Cyprus, in sector E37-E39; and, Germany, in sector C20. It is also important to mention that Germany, the United Kingdom, Italy and France occupies 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 with 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 sector E37-E39 is related to the 3rd place it occupies in electricity generation from biogas in EU28. Finally, the first place of France in sector C20 is related with its role in the chemicals industry.

Table 30. TOP 5 increasing sectors - indirect consumption supply chain

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

Source: Authors' own calculations

Table 31. TOP 5 decreasing sectors - indirect consumption supply chain

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

Source: Authors' own calculations

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5. Conclusions

This work established a methodological framework which allows performing an eco-efficiency assessment of the electricity sector in EU28 taking into account 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, encompassing the evaluation of the direct production chain, the direct and indirect consumption supply chains, using sector D35 as a proxy for the electricity sector.

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 in 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 see 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, despite the fact that 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 of labour productivity and a reduction of emissions at 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 of the GVA at the cost of a reduction on the environmental performance. In this assessment we were able to find that the top 3 countries considered as benchmarks in 2010 were Luxemburg, Denmark and Sweden and, in 2014, Luxemburg was replaced by Cyprus.

Finally, the lowest efficiency scores in this period of time 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, Lithuania, that remained inefficient, and Belgium, Cyprus, France and United Kingdom, that remained efficient. The top 5 sectors with the highest direct contribution to the emissions of the electricity sector were, in increasing 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. However, sector E37-E39 had the most important impact on the reduction of emissions in Cyprus in this period of time. This outcome is consistent with the reduction of the value of the FiT given to biogas for electricity production and the increase of the FiT given to wind and solar electricity generation. In the case of Croatia, the biggest contribution in terms of its environmental performance, beyond sector D35, is obtained from sectors C19 and B, reflecting the importance of the mineral industry in its economy.

In what concerns the indirect consumption supply chain the efficiency scores also had a reduction. In the case of efficient countries, this behaviour was a result of a mild reduction of emissions and labour at the expense of a slight reduction of GVA. In the remaining situations this was a result of a small increase of GVA at the cost of a mild increase of labour, despite the reduction of emissions. The top 3 countries considered as benchmarks in 2010 were Sweden, Luxemburg and Austria, and, in 2014, Austria was replaced by Ireland. The countries with the lowest efficiency scores were Bulgaria, Estonia, Hungary and Romania. From 2010 to 2014, Italy and Malta lost their efficiency status whereas Ireland and Belgium became efficient in 2014, and Bulgaria, Croatia, Cyprus, Estonia, Poland, Romania, Slovenia, United Kingdom and France increased their efficiency. France is the only efficient country that increased its efficiency in the indirect consumption supply chain in this period of time. The top 5 sectors with the biggest direct 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; of the EU ETS crisis which led to the significant roll out of the renewable energies in electricity generation leading to the stagnation of emission reductions (European Commission, 2018; Fabra et al., 2015); and due to the change of state aid policies in the remuneration system for renewables (Appunn, 2014; Fabra et al., 2015).

The sectors mainly responsible for the decrease on environmental performance in both direct consumption supply chain and indirect consumption supply chain were sectors A01 and H51. In this context, Italy was the country with the highest emission contributions to the electricity sector. The reason for that is that Italy is one of the biggest producers of electricity from biomass, which increased 98% during the period under analysis. On the other hand, the sectors with the biggest reduction of emissions in the direct consumption supply chain were sectors D35, B, E37-E39, C19 and C20, whereas in the indirect consumption supply chain we had the same sectors with the exception of C19 which is replaced by C23. In the case of the direct consumption supply chain, the United Kingdom, France and Germany (the leader in emission contributions) had the biggest reduction of emissions in sector D35, as a consequence of the reduction in energy consumption in EU28 along with an increase of renewable generation and a decrease of fossil fuel generation. It is also worth mentioning that the United Kingdom leads emission contributions of sector B alongside with Poland, due to their important role in natural gas and coal production, in Europe, respectively. Italy‘s leading position on the emission contributions from sectors E37-E39 can possibly be related to the fact that this country is one of the biggest producers of electricity generated from biogas in EU28. Spain leads the emissions produced by sector C19 since it is the biggest electricity producer using petroleum products in UE28 alongside with Italy. Finally, in the case of France, besides being one of the biggest reducer of emissions in all sectors, due to its “clean” electricity along with the reduction of 51% in energy consumption, this country leads the emission contributions of sector C20, due to the leading role in the chemicals industry. In the indirect consumption supply chain, the same conclusions can be drawn, but with the leading position of Germany in terms of emission contribution from sector C23. The leading position of Germany in this sector, either in the direct and indirect consumption supply chains can be sustained by the leading position of Germany regarding wind power, due to the manufacture of components for wind turbines. Moreover, the emissions of sector C24 are also led by Germany due to the same reason.

Taking into consideration the direct production chain and the direct and indirect consumption supply chain as a whole, 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 4 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 who invested more in renewable energy deployment efficiently, progressively replacing fossil fuel generation, increase 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 of 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 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 in order to promote the growth of eco-efficiency of the EU28 electricity sector.

- 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% due to 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 where which firstly introduced a carbon tax in 1991 with a value of 24€ per tonne of CO_2 and in 2019 achieved 114€ per tonne of CO_2 (Åkerfeldt et al., 2019).

- Strengthening cooperation between countries in order to promote a unique European electricity market. This will allow the countries with less capability of reduce their emissions from 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 competiveness of fossil fuels;
- The EU needs to strengthen the rules applied in order to achieve stringent renewable energy targets. Through this, the countries will be 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;
- Creation of ministries of energy governed by specialized people in order to promote the most suitable policies for renewable energy deployment;
- 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);
- Renewable electricity certificates, which award generator for megawatt of renewable energy produced. This certificates are purchase by stakeholder for meeting their obligations;
- Administratively set feed-in policies like feed-in premium (FiP) and auctions. The FiP could 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, could be used for large projects ensuring more transparency for investors and helping to discover the prices of the technology in bidding;

- Net Metering and Net Billing in distributed generation. The former, offers compensation in credits of kWh to the producer while the later 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 for utility's 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 that periods;
- Fiscal and financial incentives coupled with a strict monitoring and harsh penalties for controlling corruption or failures with agreed contractual assumptions in renewable energy generation;
- Awareness programs on the renewable energy benefits for population aimed to educate consumers for the benefits of renewable energy for economic development, greenhouse gases emissions reduction, air-quality improvement. These programs will lead them to make an aware choice in their sources of electricity generation, encouraging them to invest 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 found throughout this work is also the absence of more updated data for the IO tables.

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. It would also be interesting to make a projection of these studies for the years of 2030 and 2050 in order to understand whether the path to be taken by the EU is in line with the proposed targets or what adaptations should be made to achieve them.

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Reference List

Andersen, P., & Petersen, N. C. (1993). A Procedure for Ranking Efficient Units in Data Envelopment Analysis. Management Science, 39(10), 1261–1264. https://doi.org/10.1287/mnsc.39.10.1261

Åkerfeldt, S., Hansson, M.-O., & Waluszewski, D. (2019). Sweden ' s carbon tax. Retrieved August 10, 2019, from https://www.government.se/government-policy/taxes-and-tariffs/swedens-carbon-tax/

Appunn, K. (2014). Comparing old and new: Changes to Germany's Renewable Energy Act | Clean Energy Wire. Retrieved August 4, 2019, from https://www.cleanenergywire.org/factsheets/comparing-old-and-new-changes-germanys-renewable-energy-act

Arabi, B., Munisamy, S., & Emrouznejad, A. (2015). A new slacks-based measure of Malmquist-Luenberger index in the presence of undesirable outputs. Omega (United Kingdom), 51, 29–37. https://doi.org/10.1016/j.omega.2014.08.006

Bai-Chen, X., Ying, F., & Qian-Qian, Q. (2012). Does generation form influence environmental efficiency performance? An analysis of China's power system. Applied Energy, 96, 261–271. https://doi.org/10.1016/j.apenergy.2011.11.011

Banker, R. D. (1984). Estimating most productive scale size using data envelopment analysis. European Journal of Operational Research, 17(1), 35-44. https://doi.org/ 10.1016/0377-2217(84)90006-7.

Bi, G. B., Song, W., Zhou, P., & Liang, L. (2014). Does environmental regulation affect energy efficiency in China's thermal power generationα Empirical evidence from a slacks-based DEA model. Energy Policy, 66, 537–546. https://doi.org/10.1016/j.enpol.2013.10.056.

Brown, T. J., Hobbs, S. F., Idoine, N. E., Mills, A. J., Wrighton, C. E., & Raycraft, E. R. (2016). European Mineral Satistics 2010-14. British Geological Survey. Nottingham.

Charnes, A., Cooper, W. W., & Rhodes, E. (1978). Measuring the efficiency of decision making units. European Journal of Operational Research, 2(6), 429–444. https://doi.org/10.1016/0377-2217(78)90138-8

Cooper, W. W., Seiford, L. M., & Tone, K. (2006). Introduction to data envelopment analysis and its uses: with DEA-solver software and references. Springer Science & Business Media.

European Commission. (2018). Energy statistical datasheets for the EU countries. Retrieved March 30, 2019. Retrieved from: https://ec.europa.eu/energy/sites/ener/files/documents/countrydatasheets_august2018.xlsx

Eurostat. (2015). Electricity , gas , steam and air conditioning supply statistics - NACE Rev . 2 (Vol. 2010). Retrieved from: http://ec.europa.eu/eurostat/statisticsexplained/

EU-MERCI. (2012). Analysis of the industrial sectors in different countries: Greece, (693845), 1–36. Retrieved from http://www.eumerci-portal.eu/documents/20182/38527/3+-+Greece.pdf

Ewertowska, A., Galán-Martín, A., Guillén-Gosálbez, G., Gavaldá, J., & Jiménez, L. (2016). Assessment of the environmental efficiency of the electricity mix of the top European economies via data envelopment analysis. Journal of Cleaner Production, 116, 13–22. https://doi.org/10.1016/j.jclepro.2015.11.100

Fabra, N., Matthes, F. C., & Newbery, D. (2015). The energy transition in Europe: initial lessons from Germany, the UK and France towards to a low carbon European power sector. (Vol. 32). Retrieved from http://www.cerre.eu/sites/cerre/files/151006_CERREStudy_EnergyTransition_Final.pdf

Färe, R., & Grosskopf, S. (2010). Directional distance functions and slacks-based measures of efficiency. European Journal of Operational Research, 200(1), 320-322. doi: 10.1016/j.ejor.2010.02.033.

Fukuyama, H., & Weber, W. L. (2009). A directional slacks-based measure of technical inefficiency. Socio-Economic Planning Sciences, 43(4), 274-287. doi: 10.1016/j.seps.2008.12.001.

Gómez-Calvet, R., Conesa, D., Gómez-Calvet, A. R., & Tortosa-Ausina, E. (2014). Energy efficiency in the European Union: What can be learned from the joint application of directional distance functions and slacks-based measures? Applied Energy, 132, 137–154. https://doi.org/10.1016/j.apenergy.2014.06.053

Halkos, G. E., & Polemis, M. L. (2018). The impact of economic growth on environmental efficiency of the electricity sector: A hybrid window DEA methodology for the USA. Journal of Environmental Management, 211, 334–346. https://doi.org/10.1016/j.jenvman.2018.01.067

Halkos, G., & Petrou, K. N. (2019). Treating undesirable outputs in DEA: A critical review. Economic Analysis and Policy, 62, 97-104. doi: 10.1016/j.eap.2019.01.005.

Hastorun, S. (2016). 2014 Minerals Yearbook: Copper. USGS Mineral Resources Program, (July), 202. Retrieved from minerals.usgs.gov/minerals/pubs/commodity/bauxite/myb1-2014-bauxi.pdf

Hendrickson, C., Lave, L., & Matthews, H. (2006). Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach. Washington, USA: Resources for the Future Press.

Henriques, C. O., Coelho, D. H., Cassidy, N. L. (2016). Employment impact assessment of renewable energy targets for electricity generation by 2020 – an IO LCA approach. Sustainable Cities and Society, 26, 519-530. doi: 10.1016/j.scs.2016.05.013.

IPCC. (2018). Summary for Policymakers. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R.

Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

IRENA, OECD/IEA, & REN21. (2018). Renewable Energy Policies in a Time of Transition. Renewable Energy. Retrieved from http://www.irena.org/publications/2018/Apr/Renewable-energy-policies-in-a-time-of-transition

Korhonen, P. J., & Luptacik, M. (2004). Eco-efficiency analysis of power plants: An extension of data envelopment analysis. European Journal of Operational Research, 154(2), 437–446. https://doi.org/10.1016/S0377-2217(03)00180-2

Lábaj, M., Luptáčik, M., & Nežinský, E. (2014). Data envelopment analysis for measuring economic growth in terms of welfare beyond GDP. Empirica, 41(3), 407–424. https://doi.org/10.1007/s10663-014-9262-2

Luptacik, M., & Bohm, B. (2006). Measuring Eco-Efficiency in a Leontief Input-Output Model. International Workshop on Multiple Criteria Decision Making.

Luptacik, M., & Mahlberg, B. (2013). Eco-Efficiency and Eco-Productivity change over time in a multisectoral economic system. Department of Economic Policy - WP No. 4, (2), 1–18. https://doi.org/10.1007/s10663-014-9262-2

Miller, R., & Blair, P. (2009). Input-output analysis: foundations and extensions. New York: Cambridge University Press.

Munisamy, S., & Arabi, B. (2015). Eco-efficiency change in power plants: Using a slacks-based measure for the meta-frontier Malmquist-Luenberger productivity index. Journal of Cleaner Production, 105, 218–232. https://doi.org/10.1016/j.jclepro.2014.12.081

Nataraja, N. R., & Johnson, A. L. (2011). Guidelines for using variable selection techniques in data envelopment analysis. European Journal of Operational Research, 215(3), 662-669. https://doi.org/10.1016/j.ejor.2011.06.045

OECD. (2018). OECD Statistics. Retrieved March 27, 2018, from https://stats.oecd.org/

Sáez-Martínez, F. J., Lefebvre, G., Hernández, J. J., & Clark, J. H. (2016). Drivers of sustainable cleaner production and sustainable energy options. Journal of Cleaner Production, 138(Part 1), 1–7. https://doi.org/10.1016/j.jclepro.2016.08.094

Scarlat, N., Dallemand, J. F., & Fahl, F. (2018). Biogas: Developments and perspectives in Europe. Renewable Energy, 129, 457–472. https://doi.org/10.1016/j.renene.2018.03.006

Sueyoshi, T., & Goto, M. (2011). DEA approach for unified efficiency measurement: Assessment of Japanese fossil fuel power generation. Energy Economics, 33(2), 292–303. https://doi.org/10.1016/j.eneco.2010.07.008

Sueyoshi, T., & Goto, M. (2013). DEA environmental assessment in a time horizon: Malmquist index on fuel mix, electricity and CO2 of industrial nations. Energy Economics, 40, 370–382. https://doi.org/10.1016/j.eneco.2013.07.013

Sueyoshi, T., & Goto, M. (2018). Environmental Assessment on Energy and Sustainability by Data Envelopment Analysis. The Wiley Series in Operations Research and Management Science features. John Wiley & Sons Ltd All.

Theodoulos Mesimeris, D. of E., Nicoletta Kythreotou, D. of E., George Partasides, E. S., Katerina Piripitsi, E. S., Christina Karapitta-Zachariadou, E. S., Nikolas Hadjinikolaou, E. S., … Christodoulos Ellinopoulos, E. S. (2019). Cyprus' Integrated National Energy and Climate Plan for the, (January). Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/cyprus_draftnecp.pdf

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R., & De Vries, G. J. (2015). An illustrated user guide to the world input–output database: the case of global automotive production. Review of International Economics, 23(3), 575-605. https://doi.org/10.1111/roie.12178

Tone, K. (2001). A slacks-based measure of efficiency in data envelopment analysis. European Journal of Operational Research, 130(3), 498–509. https://doi.org/10.1016/S0377-2217(99)00407-5

Vaninsky, A. Y. (2009). Environmental efficiency of electric power industry of the United States: A data envelopment analysis approach. World Academy of Science, Engineering and Technology, 40, 584–590. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-78651570314&partnerID=40&md5=75f9a60d38705bfd3bb542bda7201f9a

Worldwide Fund for Nature. (2015). European Footprint | WWF. Retrieved April 8, 2018, from http://wwf.panda.org/what_we_do/how_we_work/policy/wwf_europe_environment/initiatives/european_footprint_/

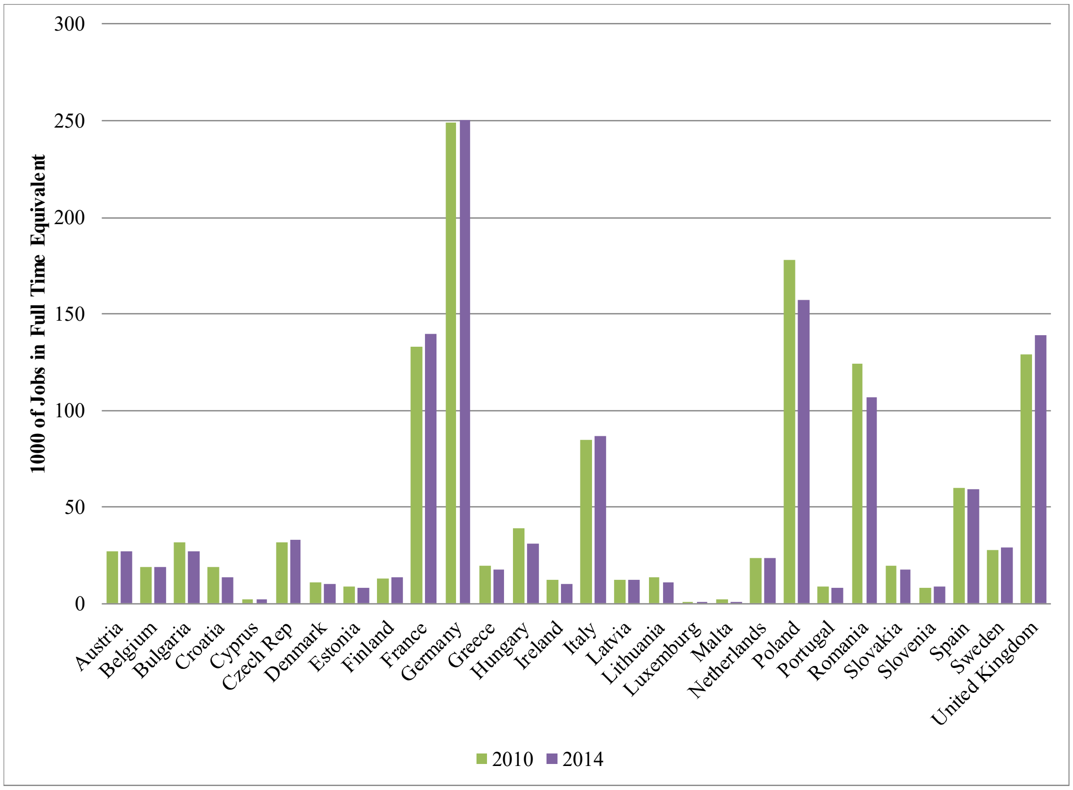
Zhang, N., & Kim, J. D. (2014). Measuring sustainability by energy efficiency analysis for Korean Power Companies: A sequential slacks-based efficiency measure. Sustainability (Switzerland), 6(3), 1414–1426. https://doi.org/10.3390/su6031414

Zurano-Cervelló, P., Pozo, C., Mateo-Sanz, J. M., Jiménez, L., & Guillén-Gosálbez, G. (2018). Eco-efficiency assessment of EU manufacturing sectors combining input-output tables and data envelopment analysis following production and consumption-based accounting approaches. Journal of Cleaner Production, 174, 1161–1189. https://doi.org/10.1016/j.jclepro.2017.10.178

APPENDIXES

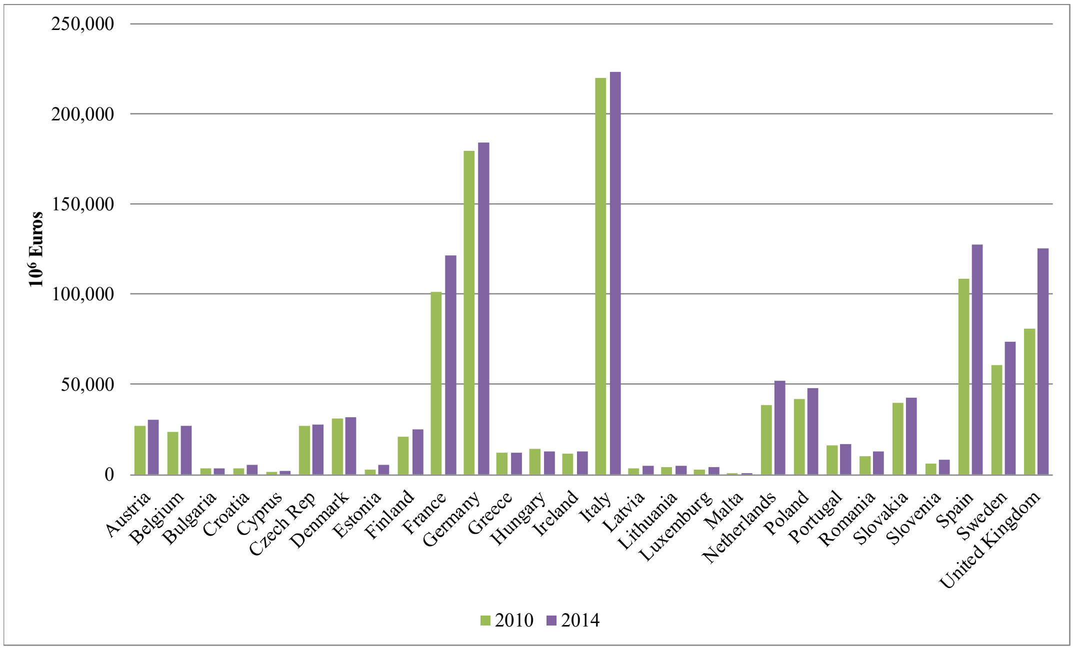
APPENDIX 1

Direct production chain inputs and outputs of the electricity sector



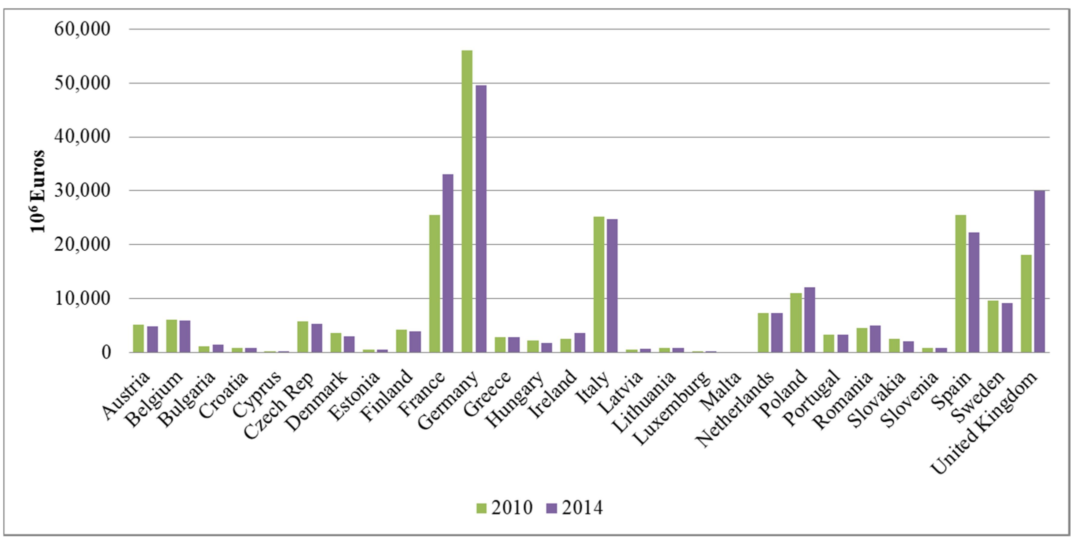
Source: Social Accounts published by the World IO database

Figure 1A. Labour used in the direct production chain of the electricity sector



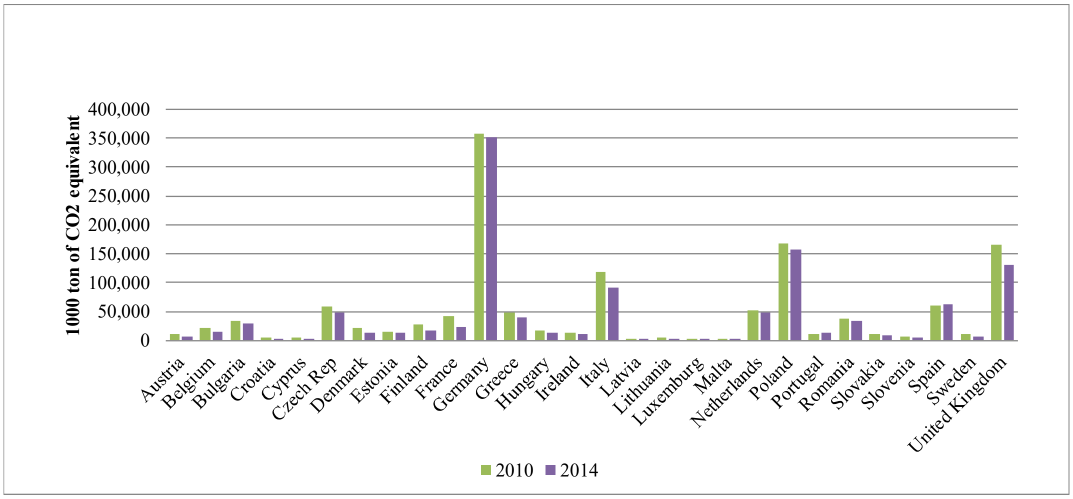
Source: Social Accounts published by the World IO database

Figure 2A. Nominal capital stock used in the direct production chain of the electricity sector



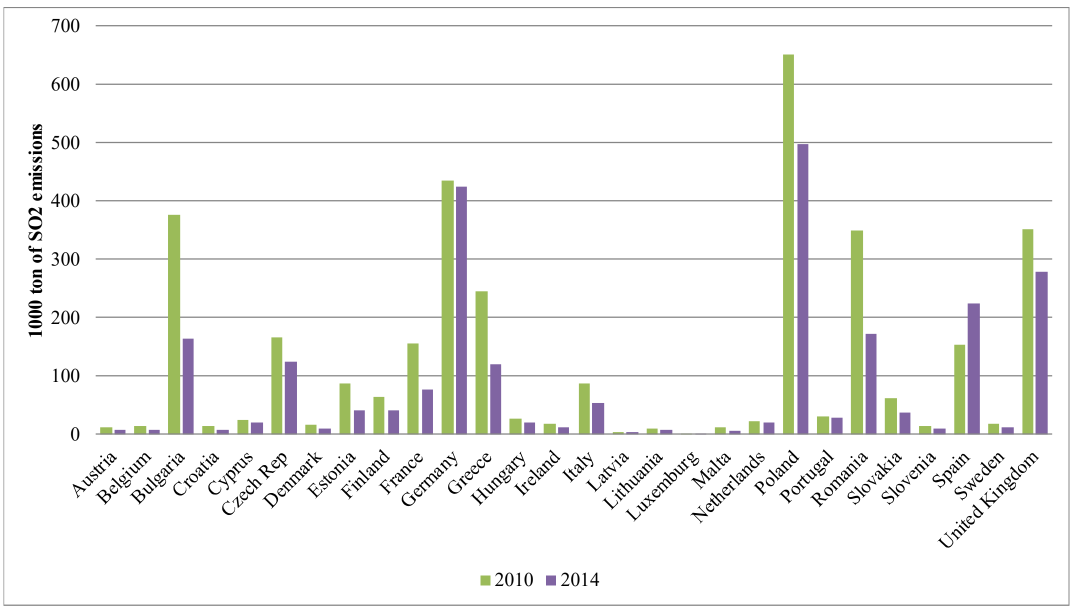
Source: Social Accounts published by the World IO database

Figure 3A. Gross Value Added produced in the direct production chain of the electricity sector



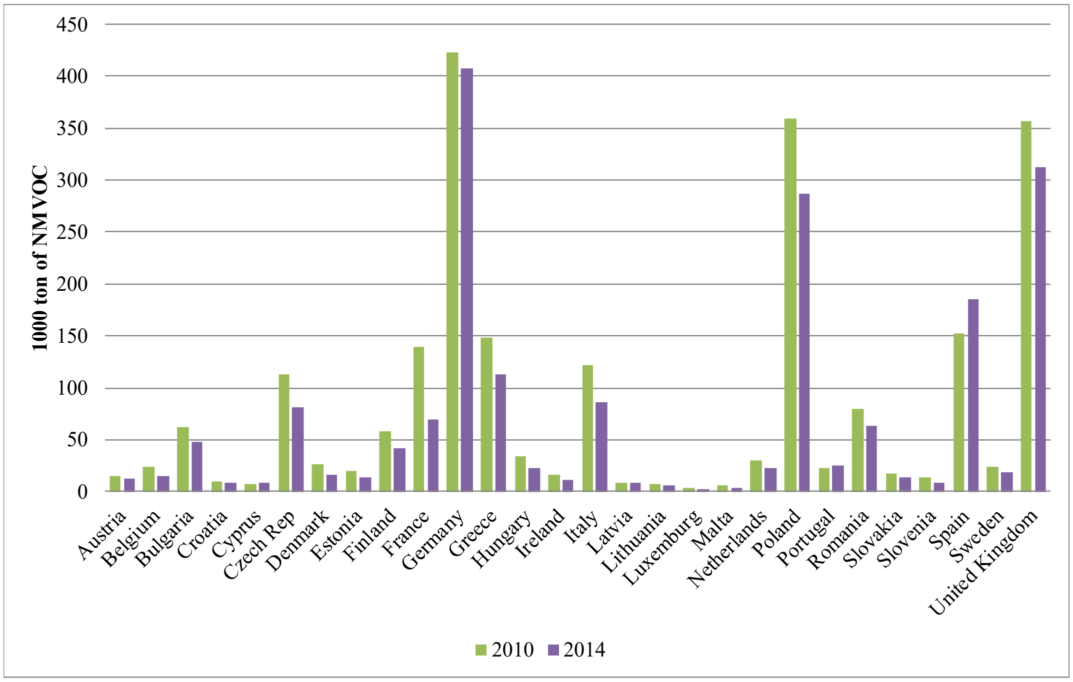
Source: Air Emission Accounts – OECD estimates

Figure 4A. GHG emissions in the direct production chain of the electricity sector



Source: Air Emission Accounts – OECD estimates

Figure 5A. ACG emissions in the direct production chain of the electricity sector



Source: Air Emission Accounts – OECD estimates

Figure 6A. O3PR emissions in the direct production chain of the electricity sector

APPENDIX 2

Consumption supply chain inputs and outputs of the sectors directly engaged in electricity production

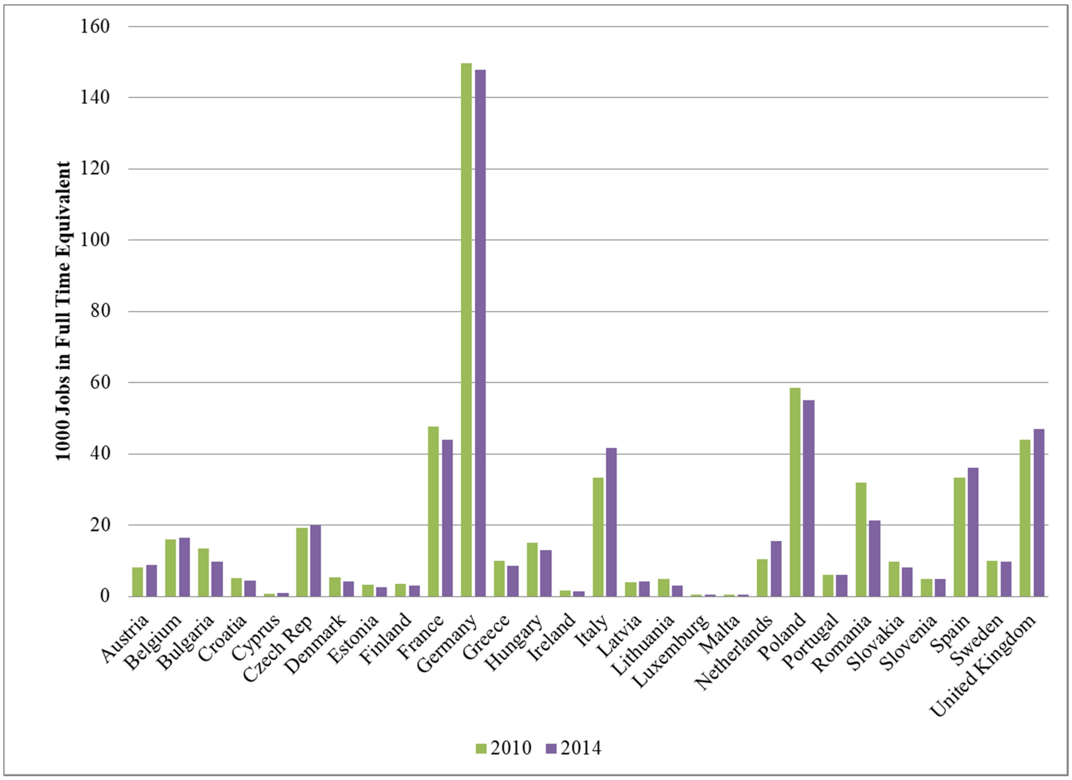


Figure 7A. Labour used in the consumption supply chain of the sectors directly engaged in electricity production

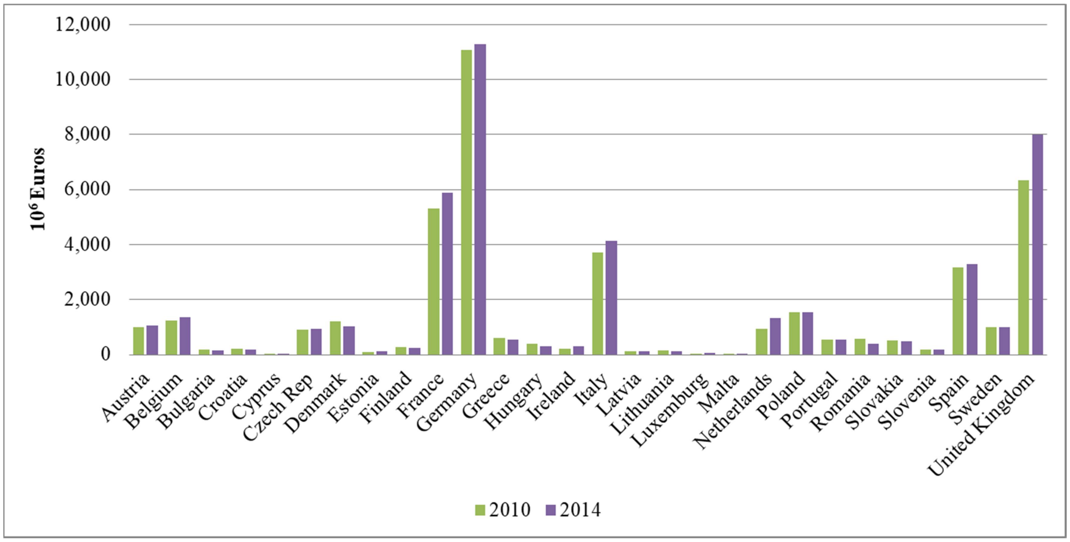


Figure 8A. Gross Value Added produced in the consumption supply chain of the sectors directly engaged in electricity production

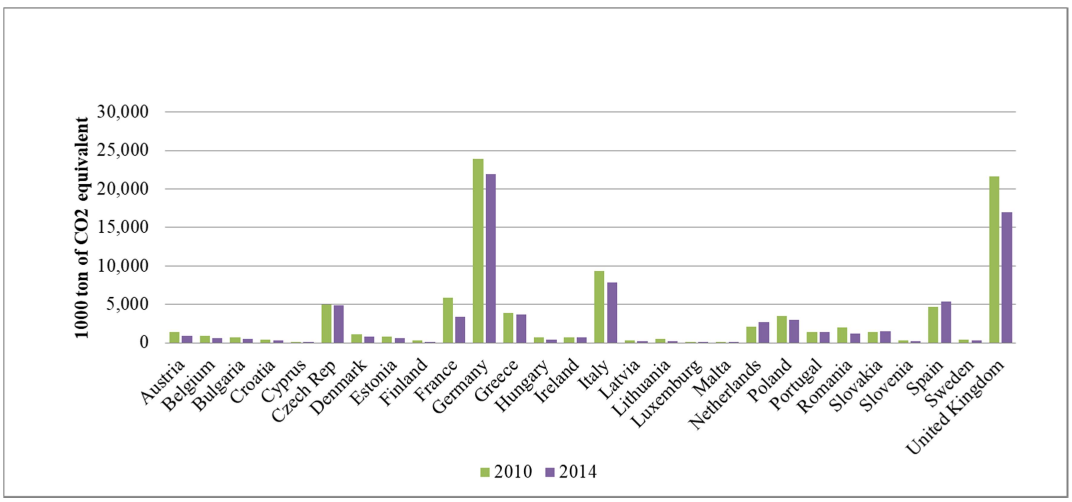


Figure 9A. GHG emissions in the consumption supply chain of the sectors directly engaged in electricity production

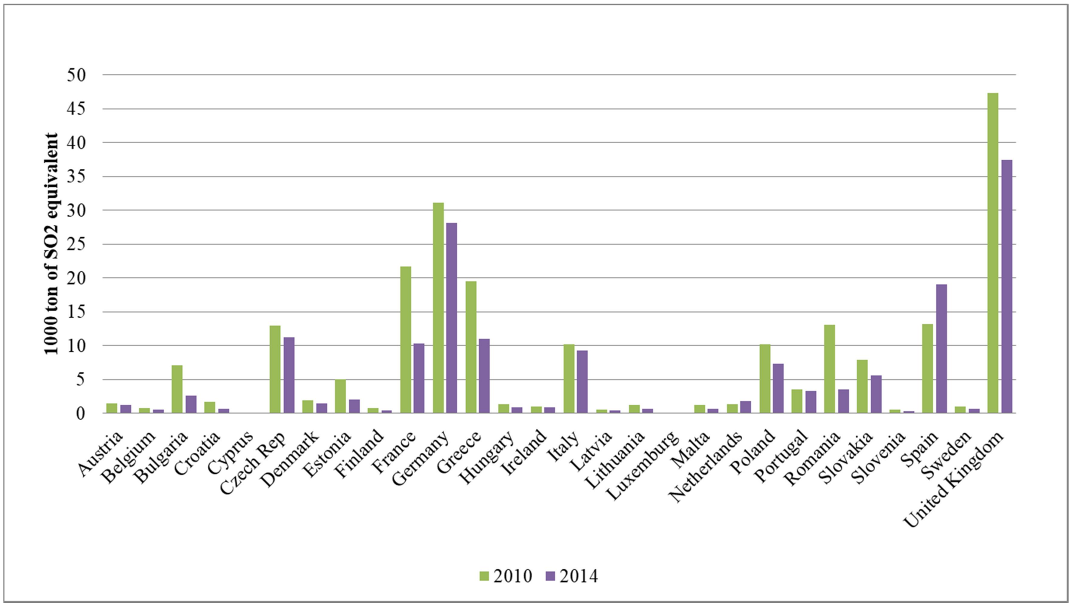


Figure 10A. ACG emissions in the consumption supply chain of the sectors directly engaged in electricity production

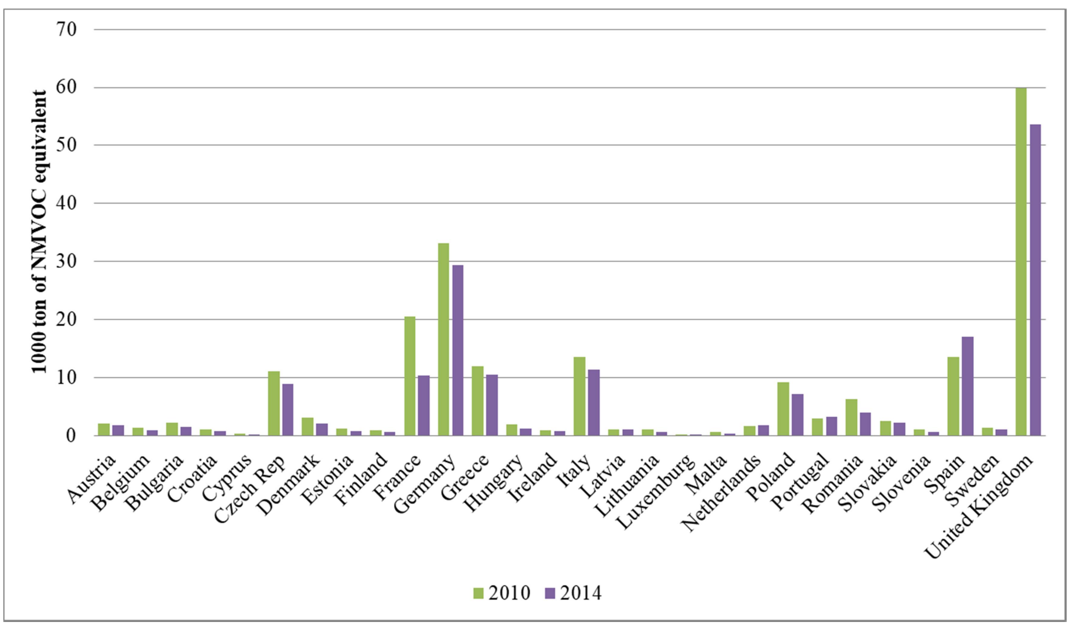


Figure 11A. O3PR emissions in the consumption supply chain of the sectors directly engaged in electricity production

APPENDIX 3

Consumption supply chain inputs and outputs of the sectors indirectly engaged in electricity production

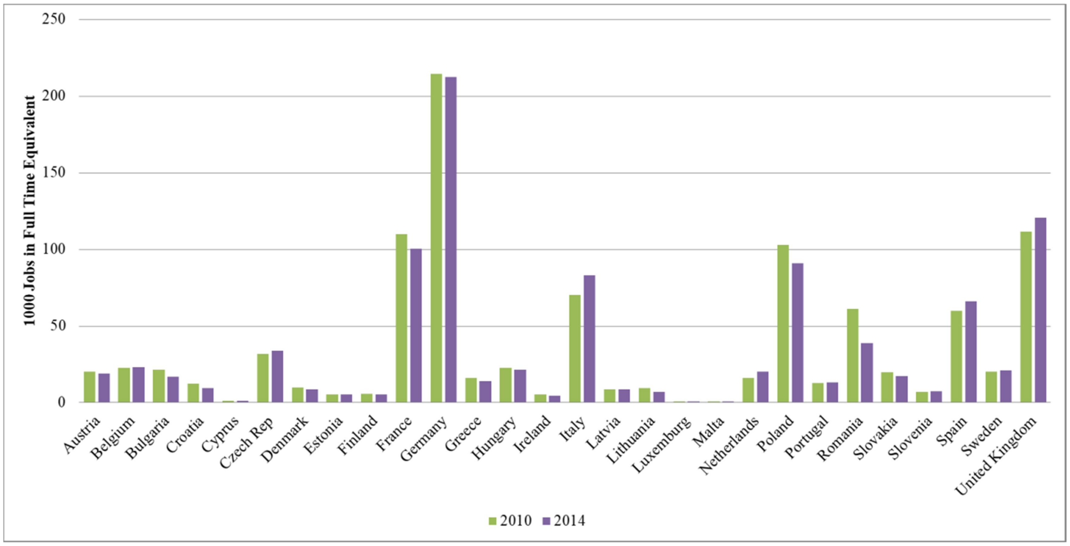


Figure 12A. Labour used in the consumption supply chain of the sectors indirectly engaged in electricity production

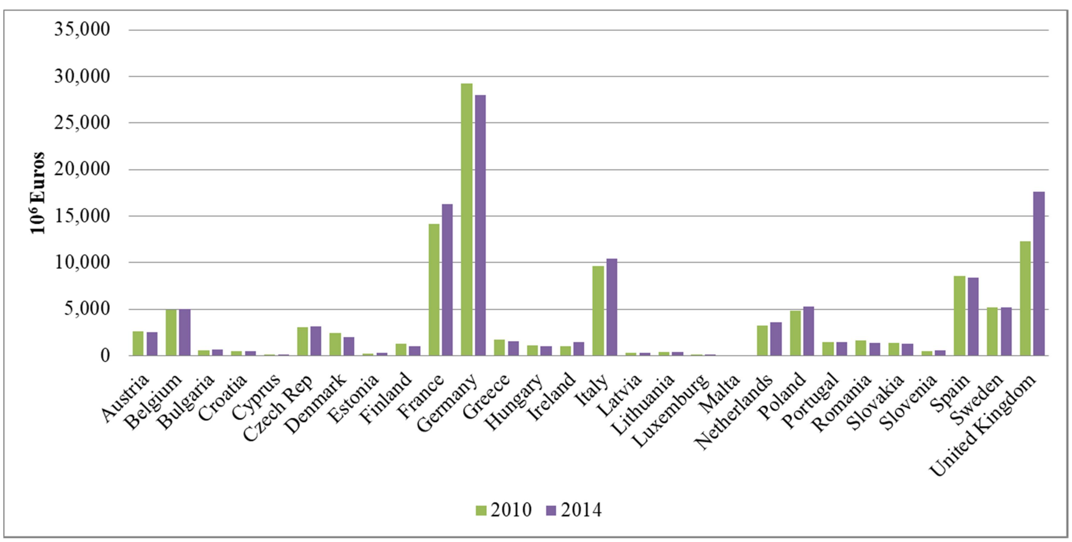


Figure 13A. Gross Value Added produced in the consumption supply chain of the sectors indirectly engaged in electricity production

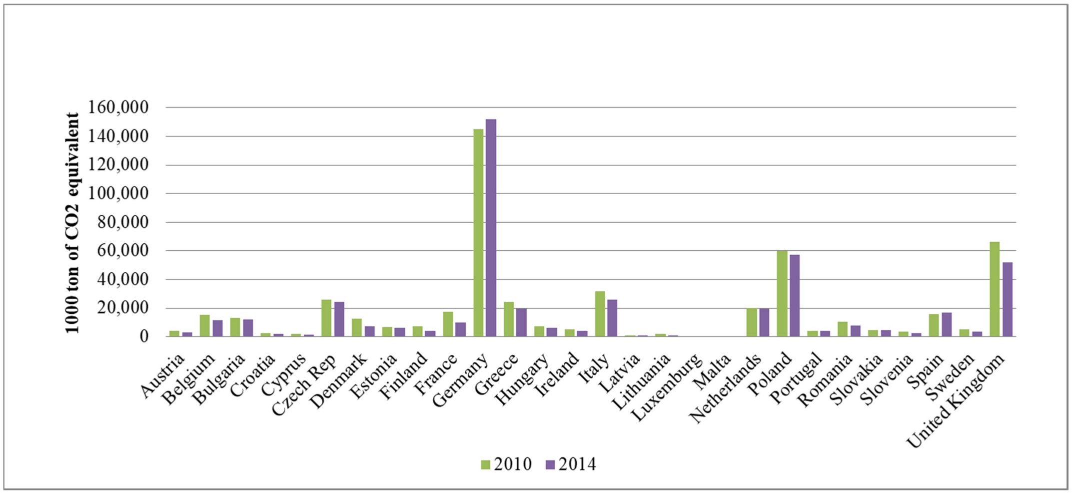


Figure 14A. GHG emissions in the consumption supply chain of the sectors indirectly engaged in electricity production

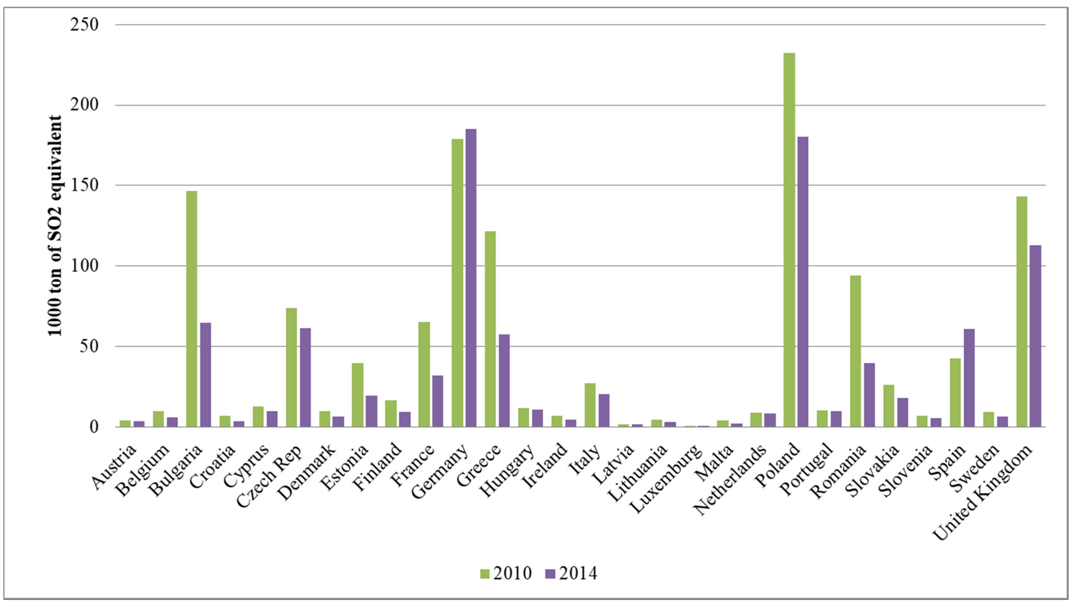


Figure 15A. ACG emissions in the consumption supply chain of the sectors indirectly engaged in electricity production

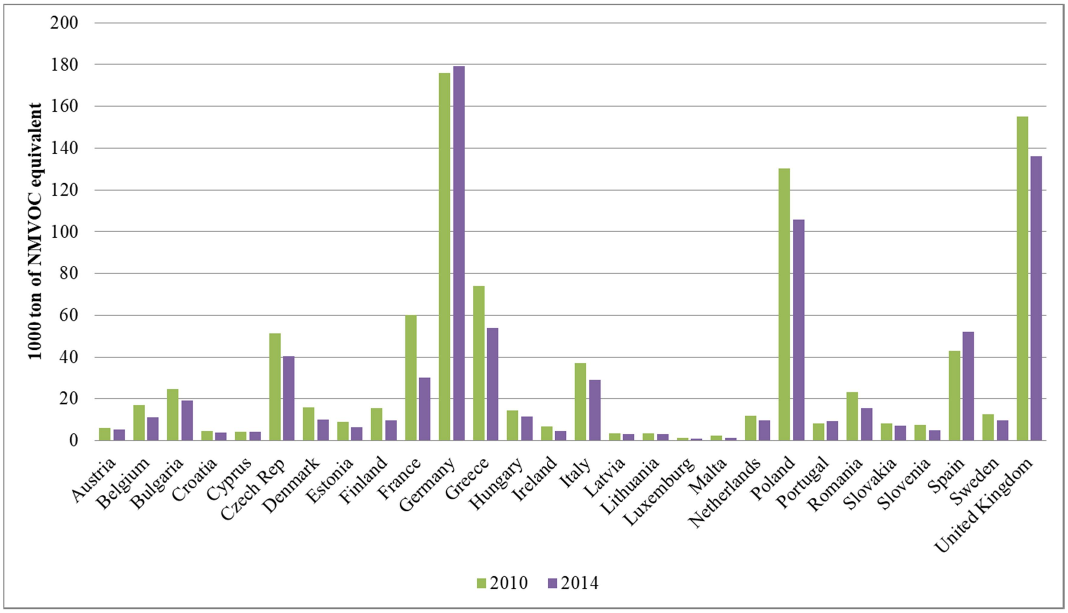
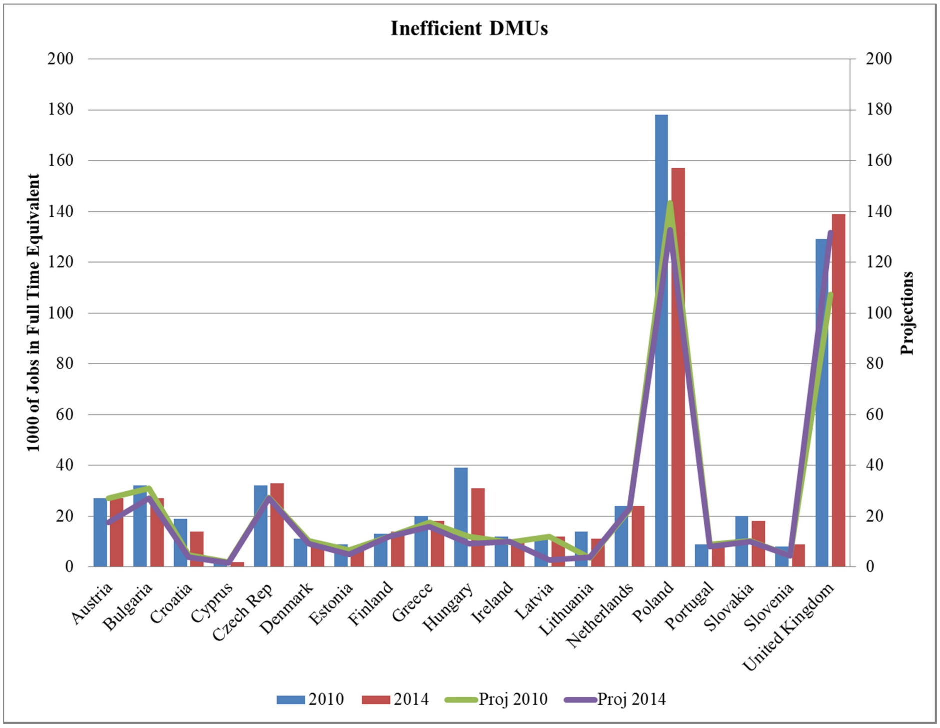


Figure 16A. O3PR emissions in the consumption supply chain of the sectors indirectly engaged in electricity production

Appendix 4

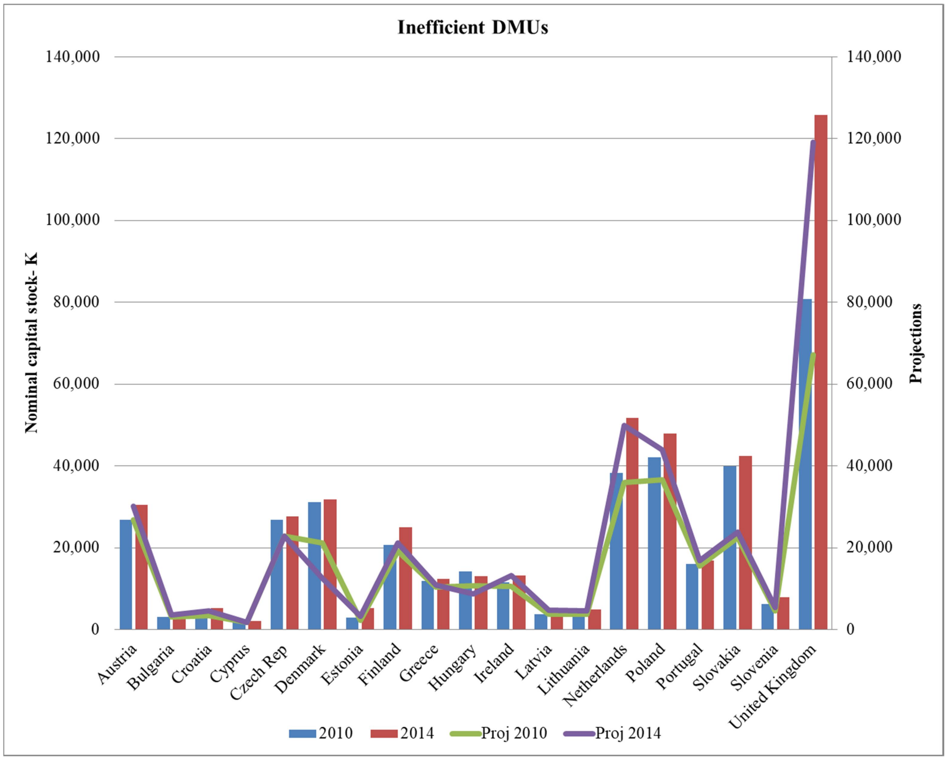
Direct production chain inputs and outputs projections of inefficient DMUs to become efficient



Source: Authors' own calculations.

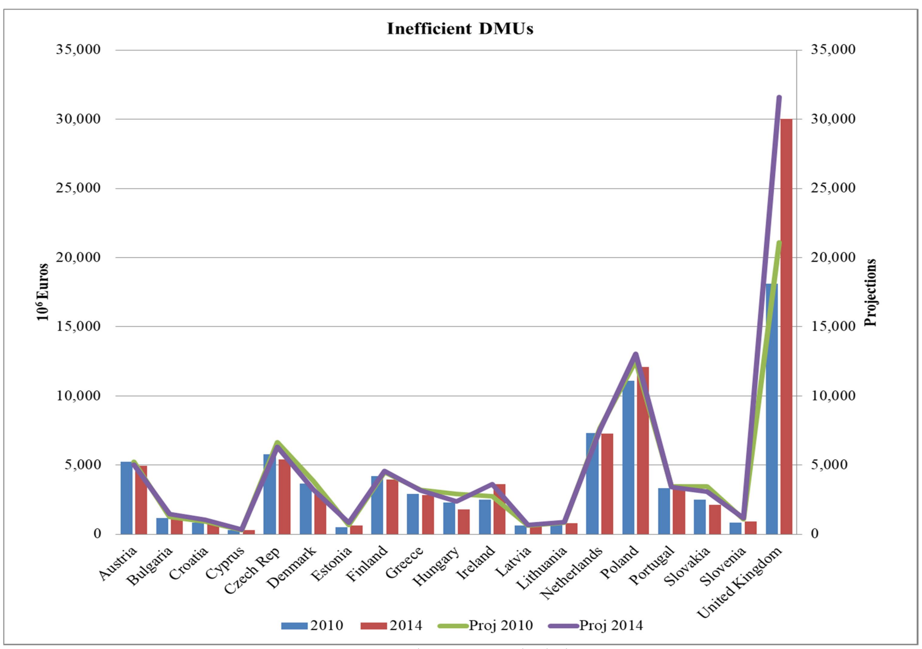
Note: Proj refers to Projection provided by the DDF model in order to become efficient

Figure 17A. Labour vs. Projections in 2010 and 2014 – direct production chain



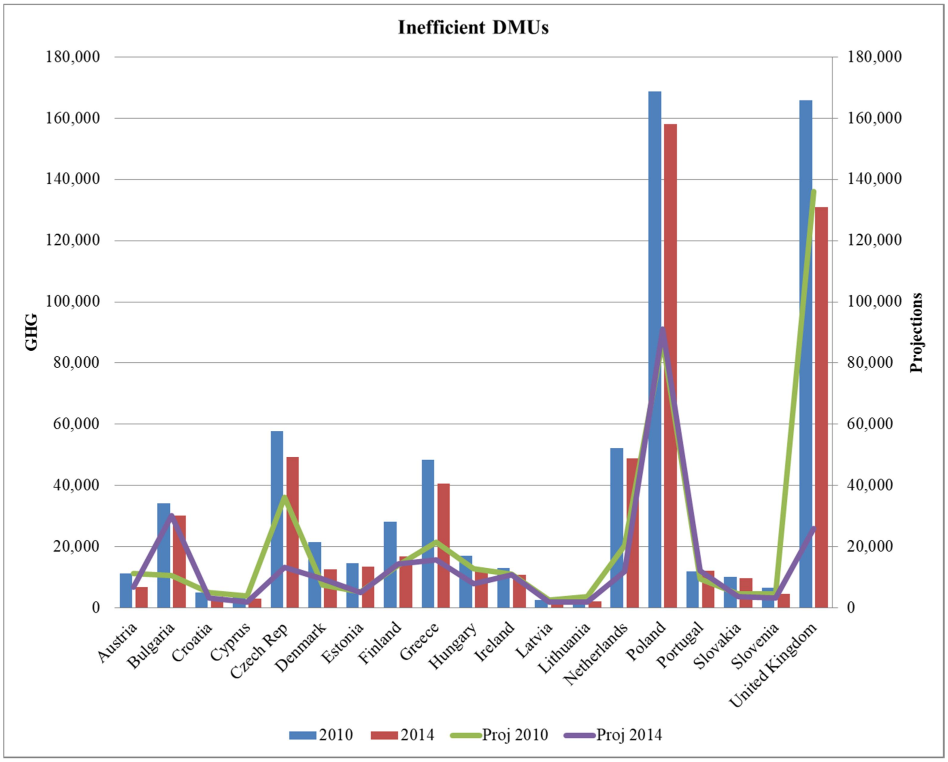
Source: Authors' own calculations.

Figure 18A. Nominal Capital Stock vs. Projections in 2010 and 2014 – direct production chain



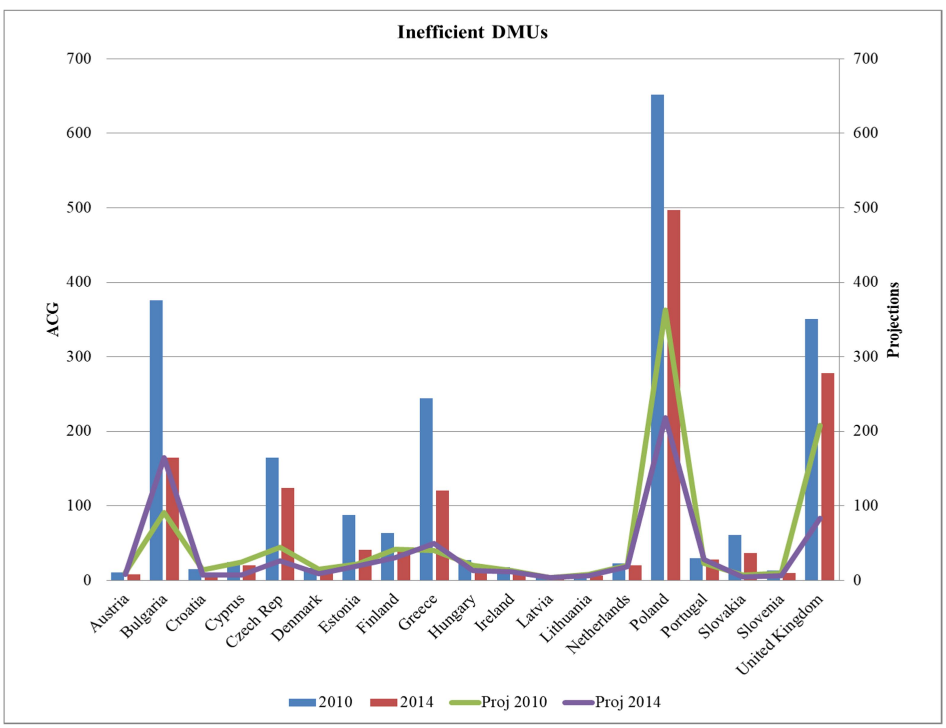
Source: Authors' own calculations.

Figure 19A. Gross Value Added vs. Projections in 2010 and 2014 - direct production chain



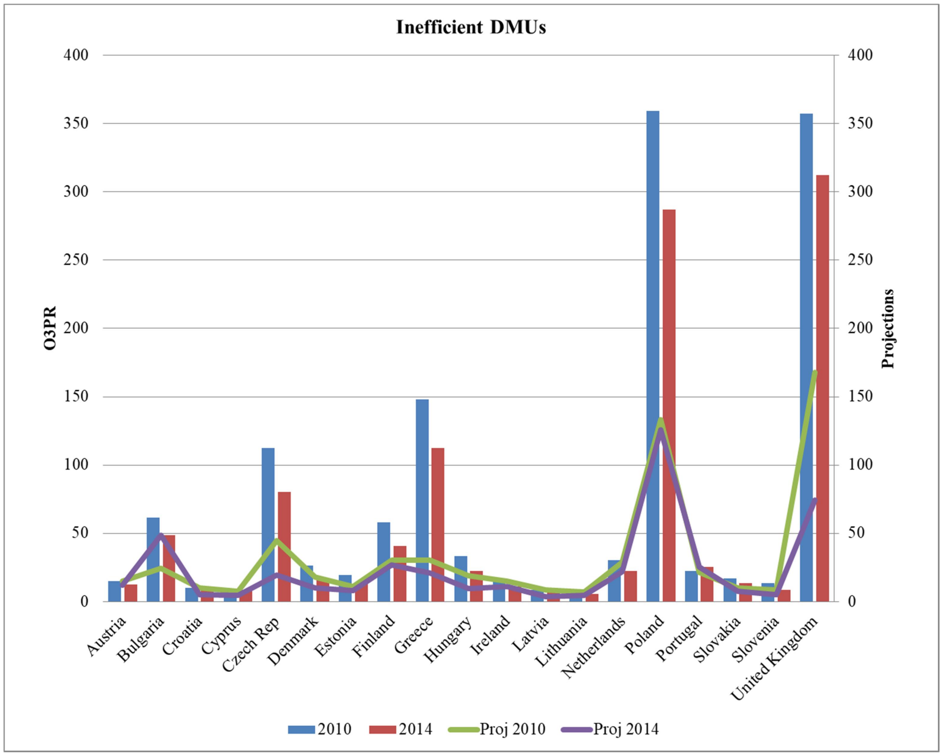
Source: Authors' own calculations.

Figure 20A. GHG vs. Projections in 2010 and 2014 – direct production chain



Source: Authors' own calculations.

Figure 21A. ACG vs. Projections in 2010 and 2014 – direct production chain

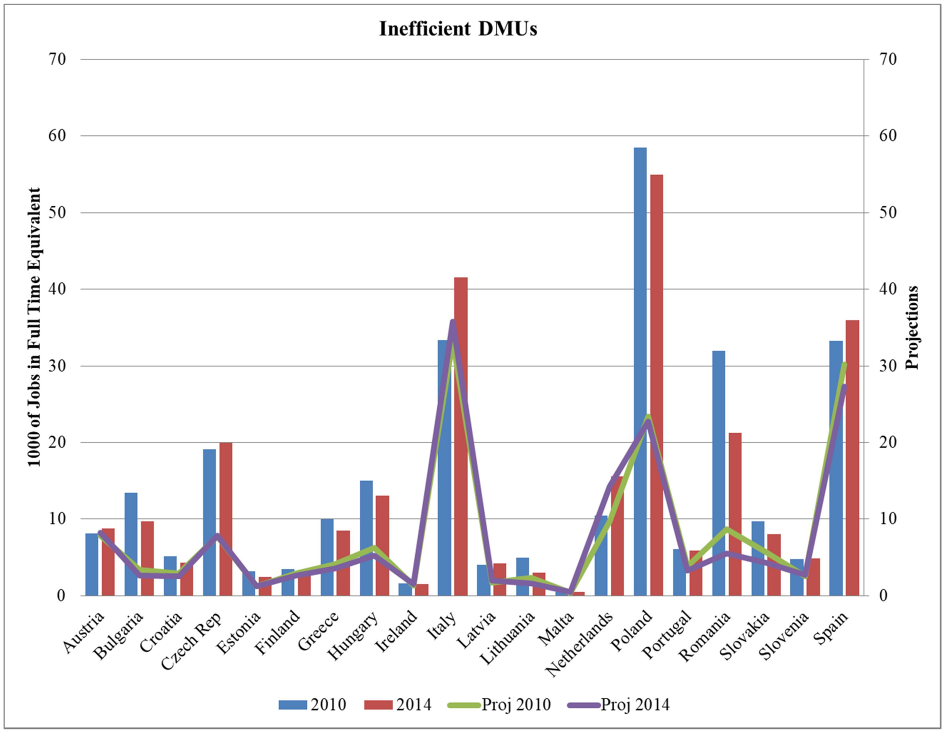


Source: Authors' own calculations.

Figure 22A. O3PR vs. Projections in 2010 and 2014 – direct production chain

APPENDIX 5

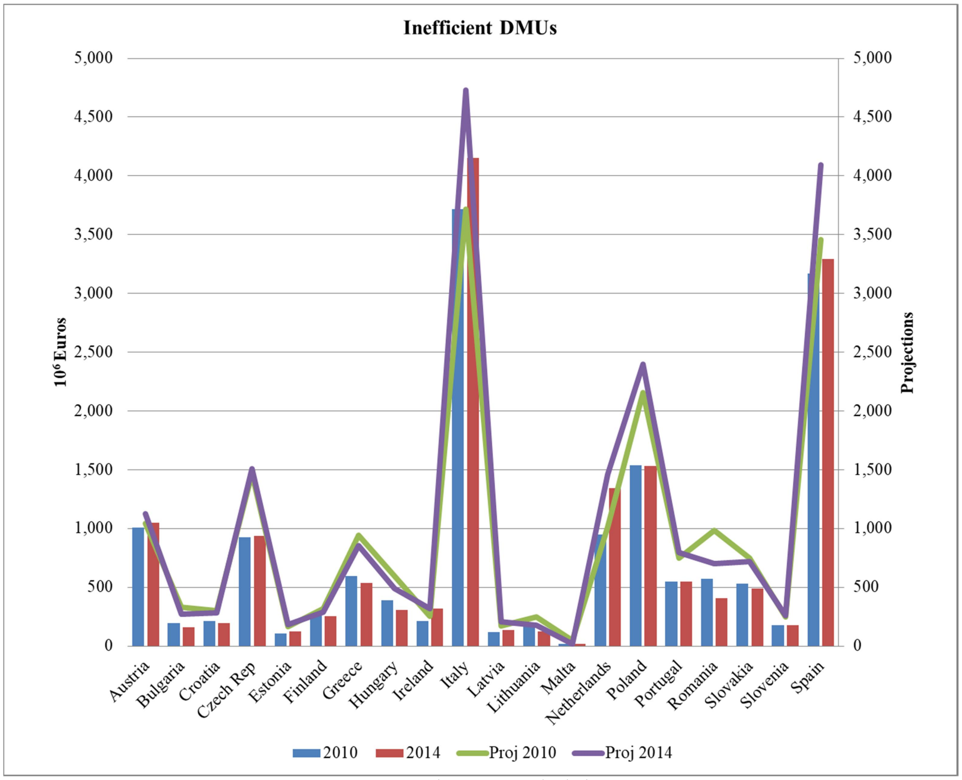
Direct consumption supply chain inputs and outputs projections of inefficient DMUs to become efficient



Source: Authors' own calculations.

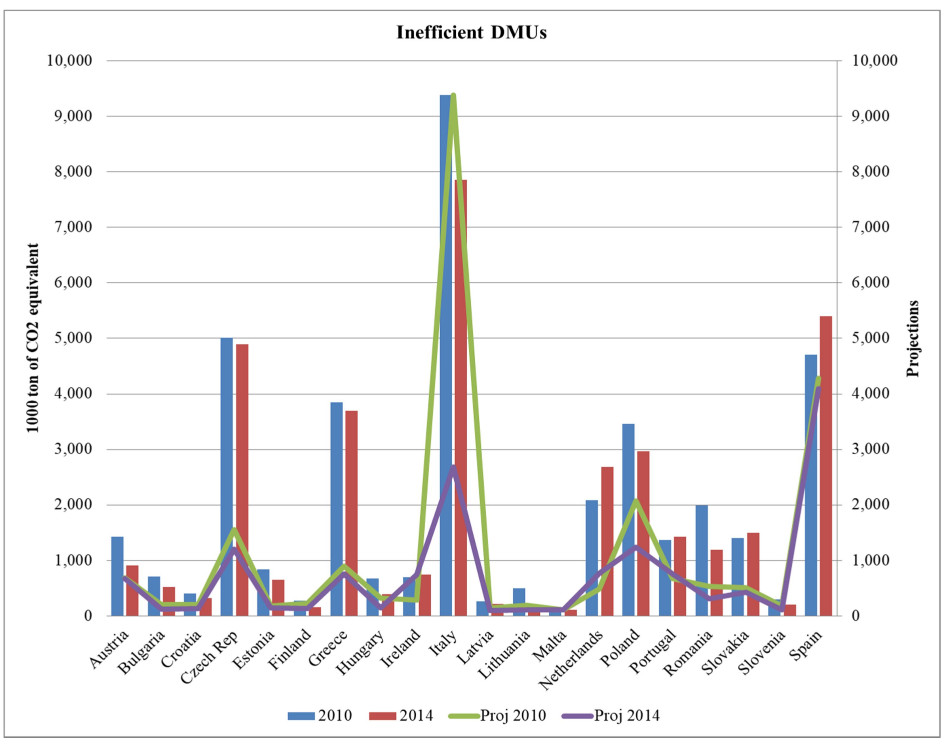
Note: Proj refers to Projection provided by the DDF model in order to become efficient

Figure 23A. Labour vs. Projections in 2010 and 2014 - direct consumption supply chain



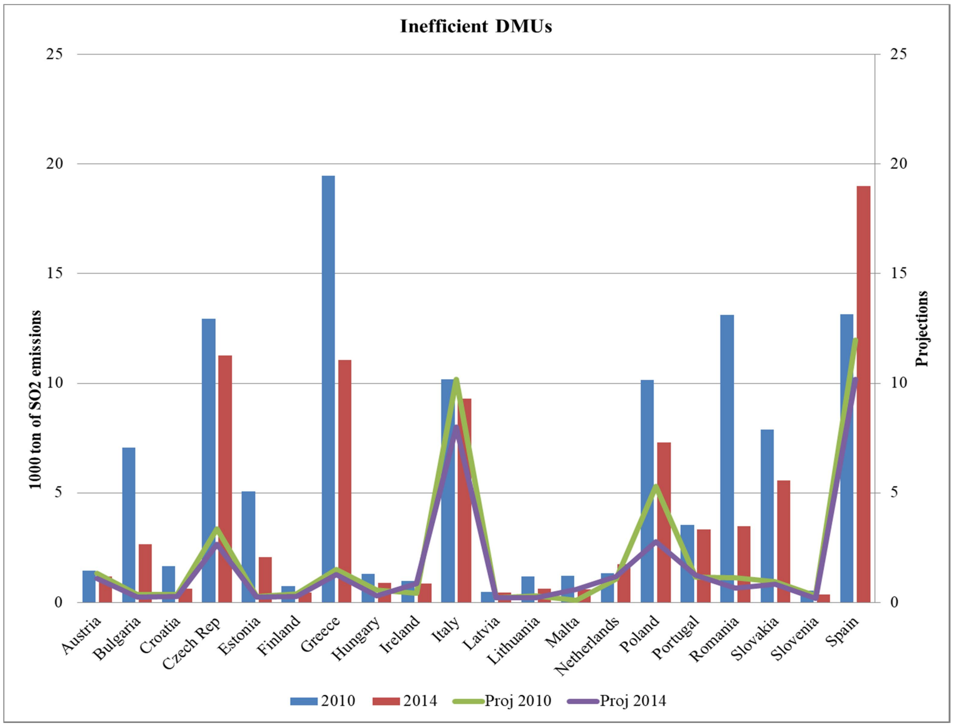
Source: Authors' own calculations.

Figure 24A. Gross Value Added vs. Projections in 2010 and 2014 - direct consumption supply chain



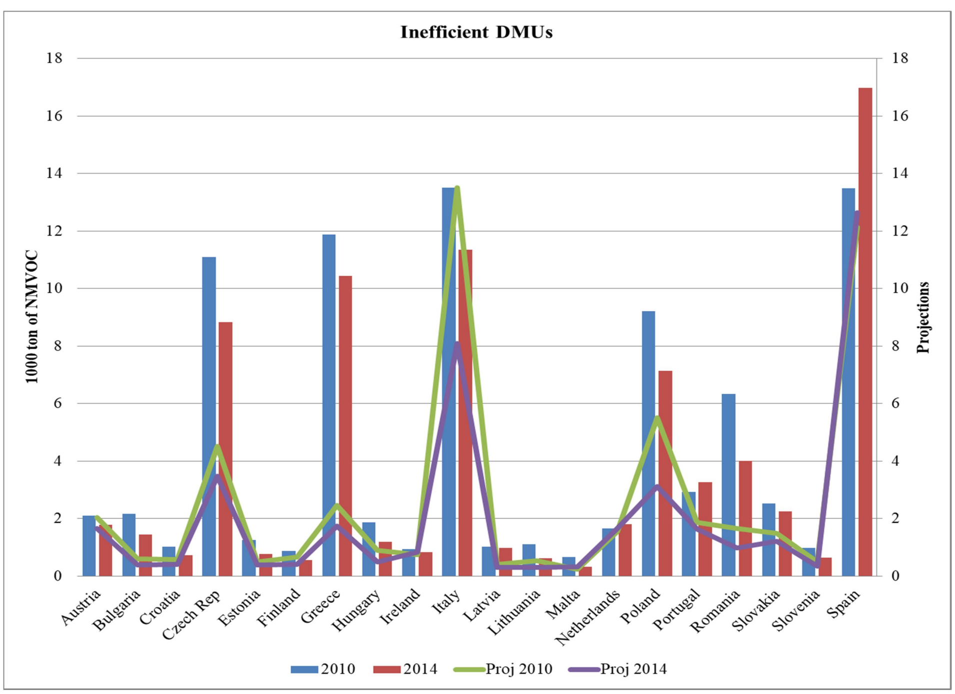
Source: Authors' own calculations.

Figure 25A. GHG vs. Projections in 2010 and 2014 - direct consumption supply chain



Source: Authors' own calculations.

Figure 26A. ACG vs. Projections in 2010 and 2014 - direct consumption supply chain

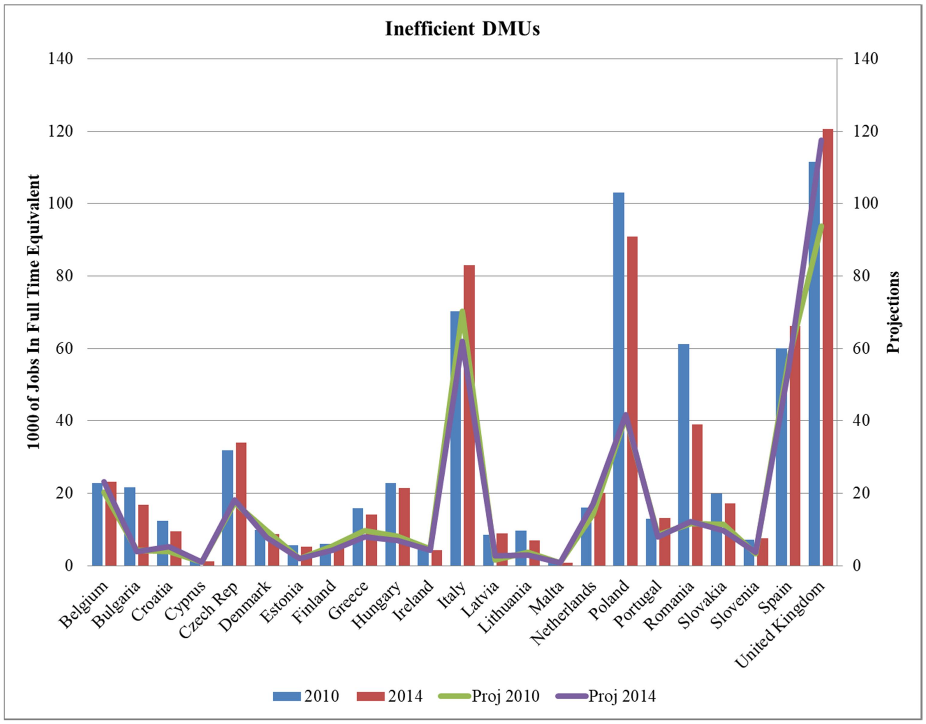


Source: Authors' own calculations.

Figure 27A. O3PR vs. Projections in 2010 and 2014 - direct consumption supply chain

Appendix 6

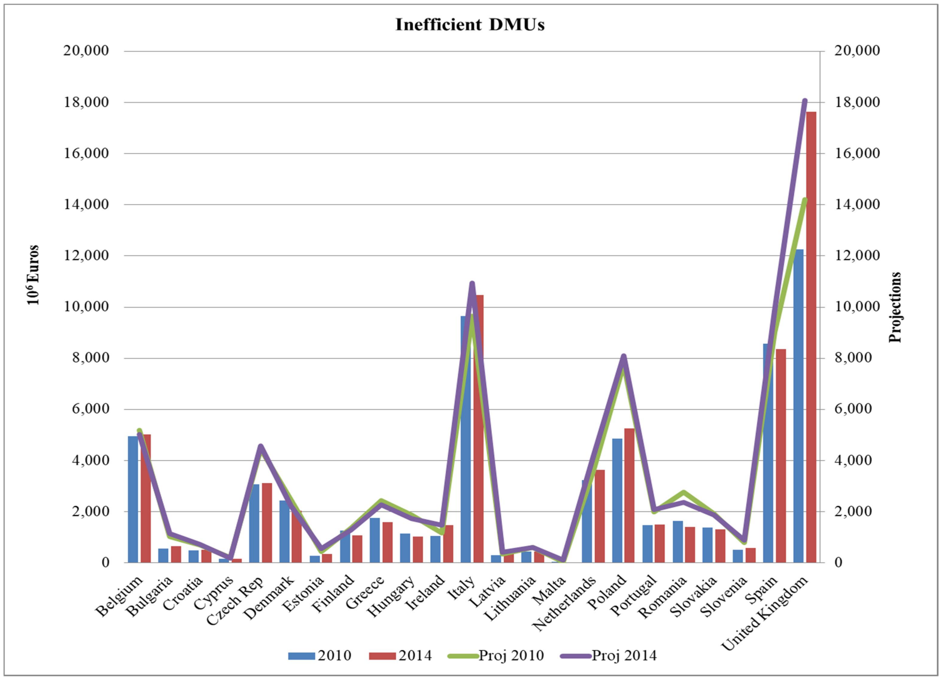
Indirect consumption supply chain inputs and outputs projections of inefficient DMUs to become efficient.



Source: Authors' own calculations.

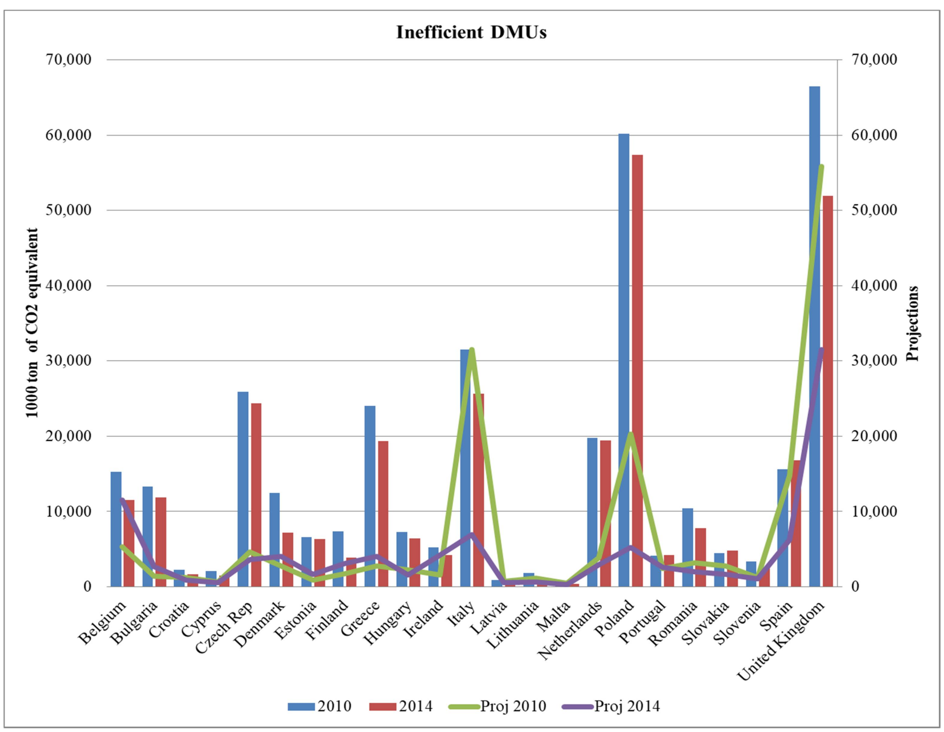
Note: Proj refers to Projection provided by the DDF model in order to become efficient

Figure 28A. Labour vs. Projections in 2010 and 2014 - indirect consumption supply chain



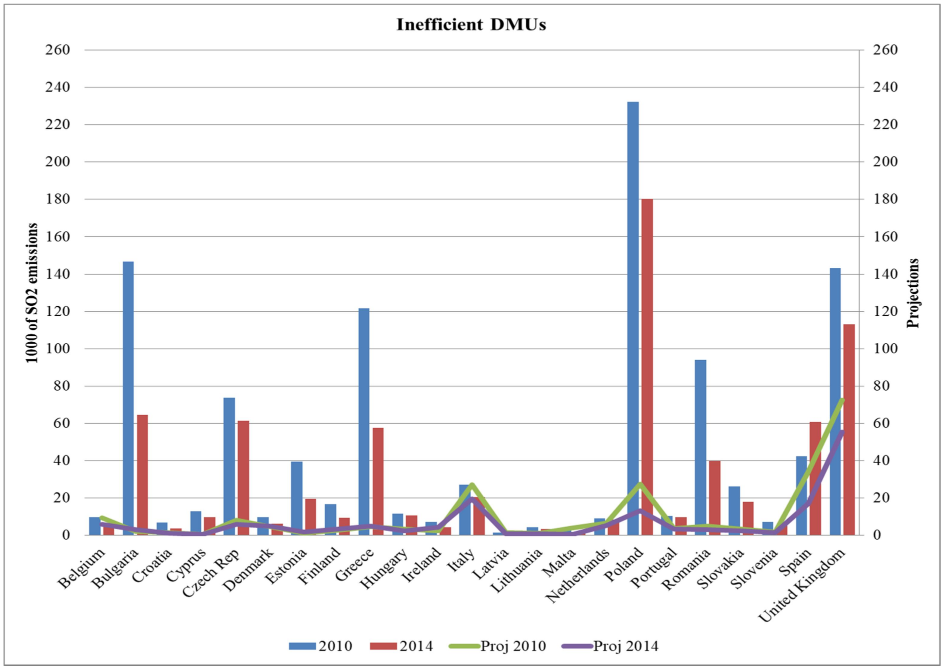
Source: Authors' own calculations.

Figure 29A. Gross Value Added vs. Projections in 2010 and 2014 - indirect consumption supply chain



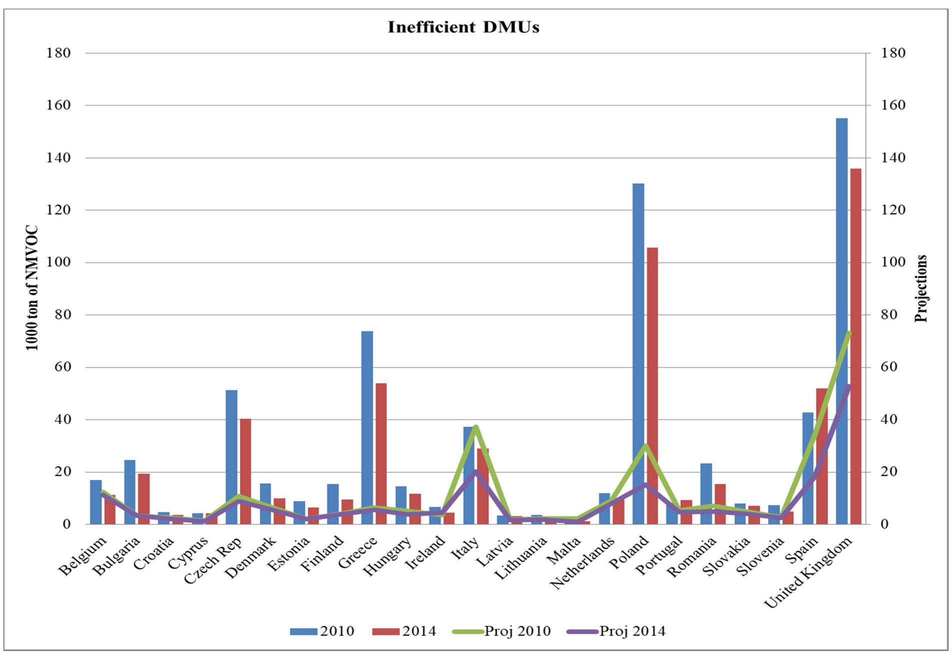
Source: Authors' own calculations.

Figure 30A. GHG vs. Projections in 2010 and 2014 - indirect consumption supply chain



Source: Authors' own calculations

Figure 31A. ACG vs. Projections in 2010 and 2014 - indirect consumption supply chain



Source: Authors' own calculations

Figure 32A. O3PR vs. Projections in 2010 and 2014 - indirect consumption supply chain

APPENDIX 7

Direct consumption supply chain thermic tables of inputs and outputs contributions by sector for electricity sector.

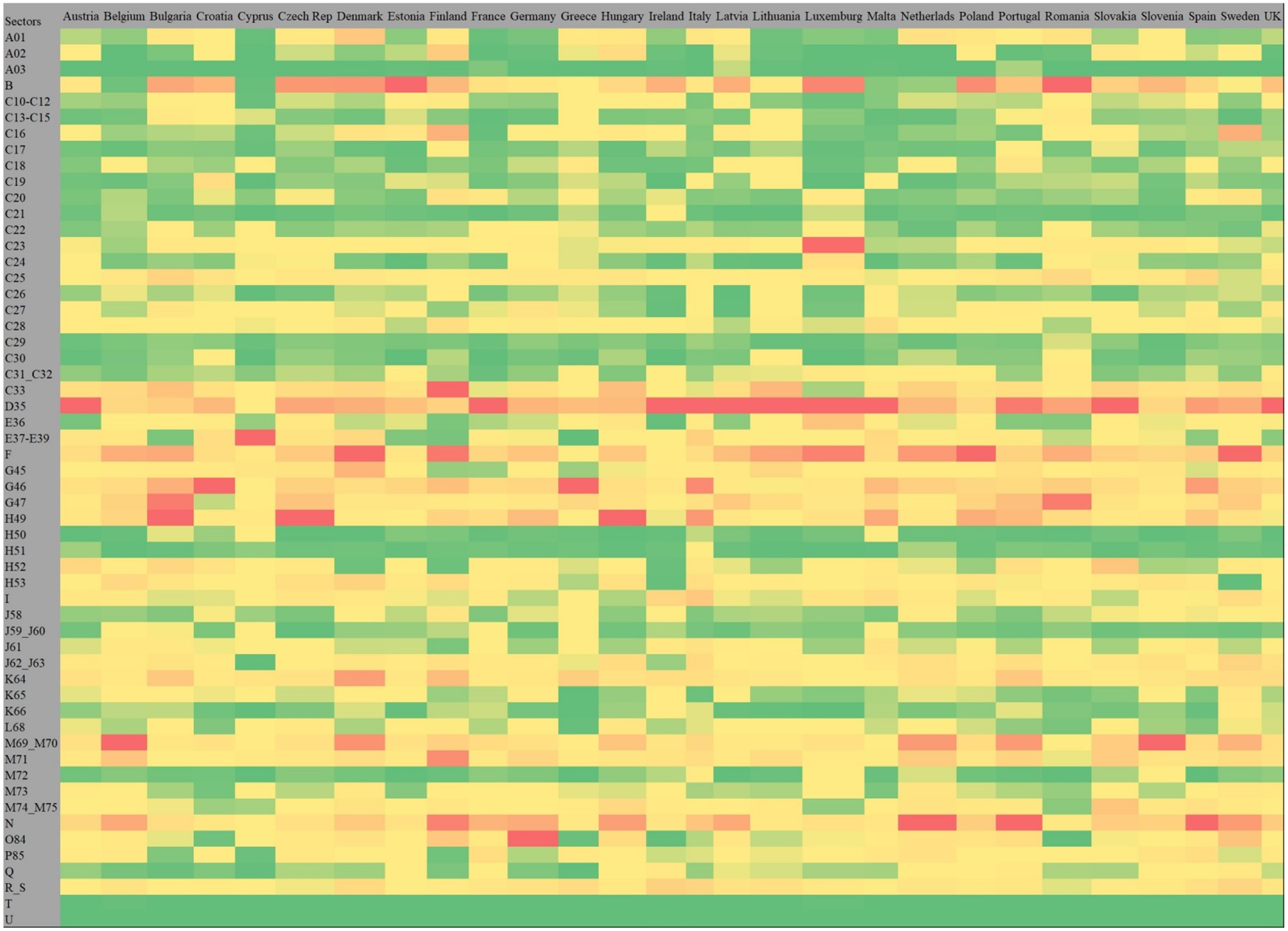


Figure 33A. Thermic tables for Labour contributions by sector for electricity sector - 2010 - direct consumption supply chain

Figure 34A. Thermic tables for Labour contributions by sector for electricity sector – 2014 - direct consumption supply chain

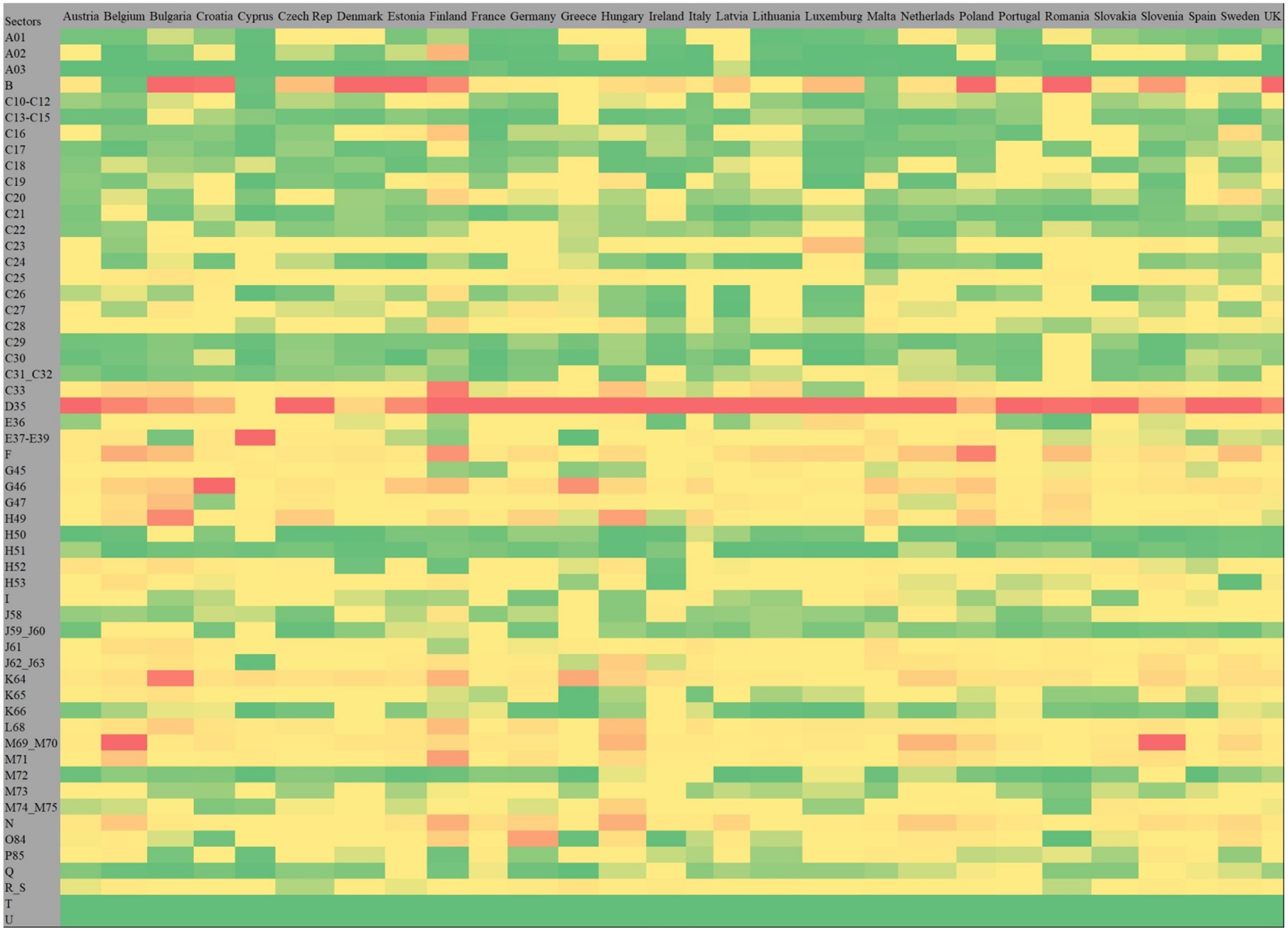


Figure 35A. Thermic tables for GVA contributions by sector for electricity sector – 2010 - direct consumption supply chain

Figure 36A. Thermic tables for GVA contributions by sector for electricity sector – 2014 - direct consumption supply chain

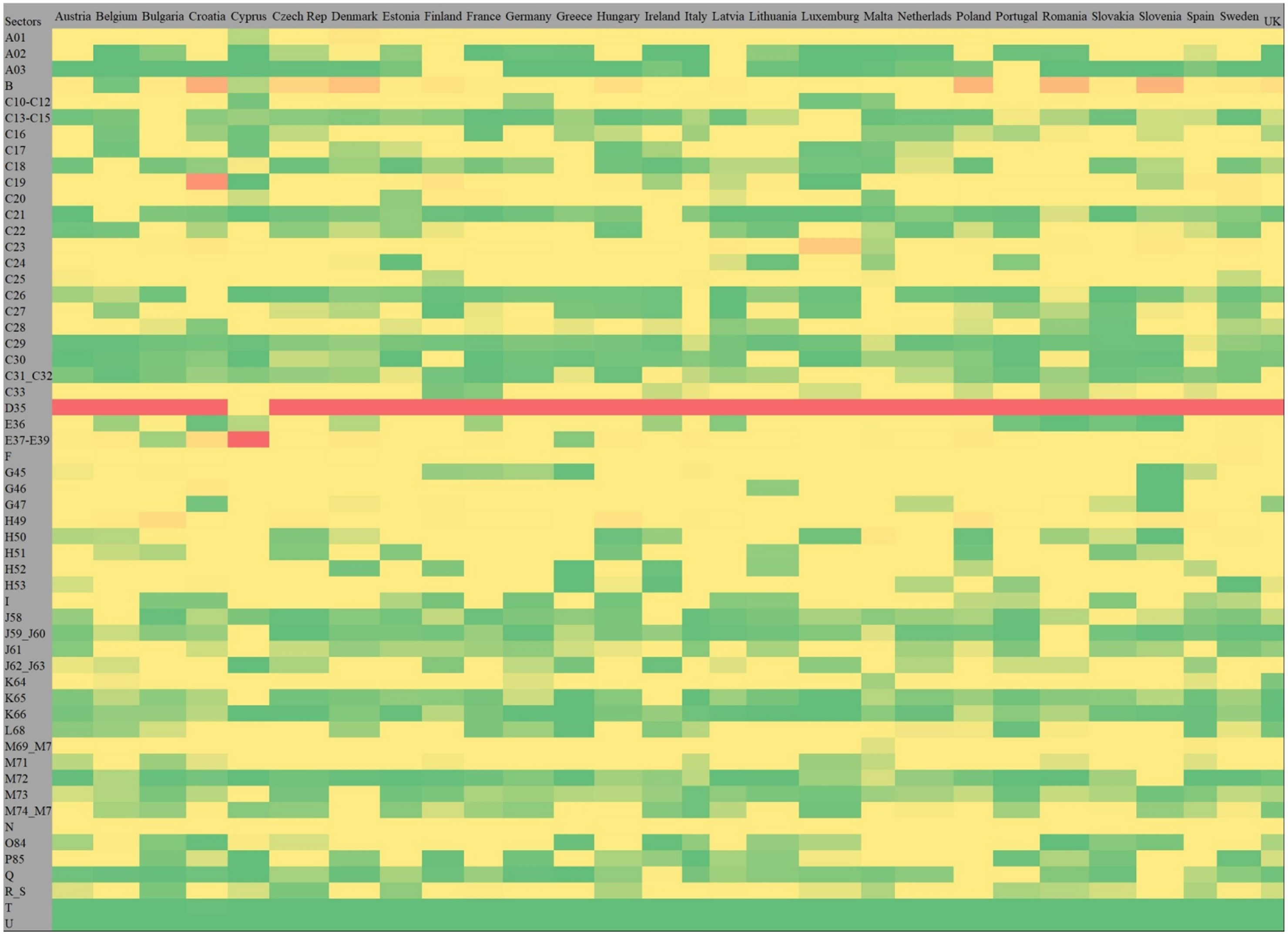


Figure 37A. Thermic tables for GHG contributions by sector for electricity sector – 2010 - direct consumption supply chain

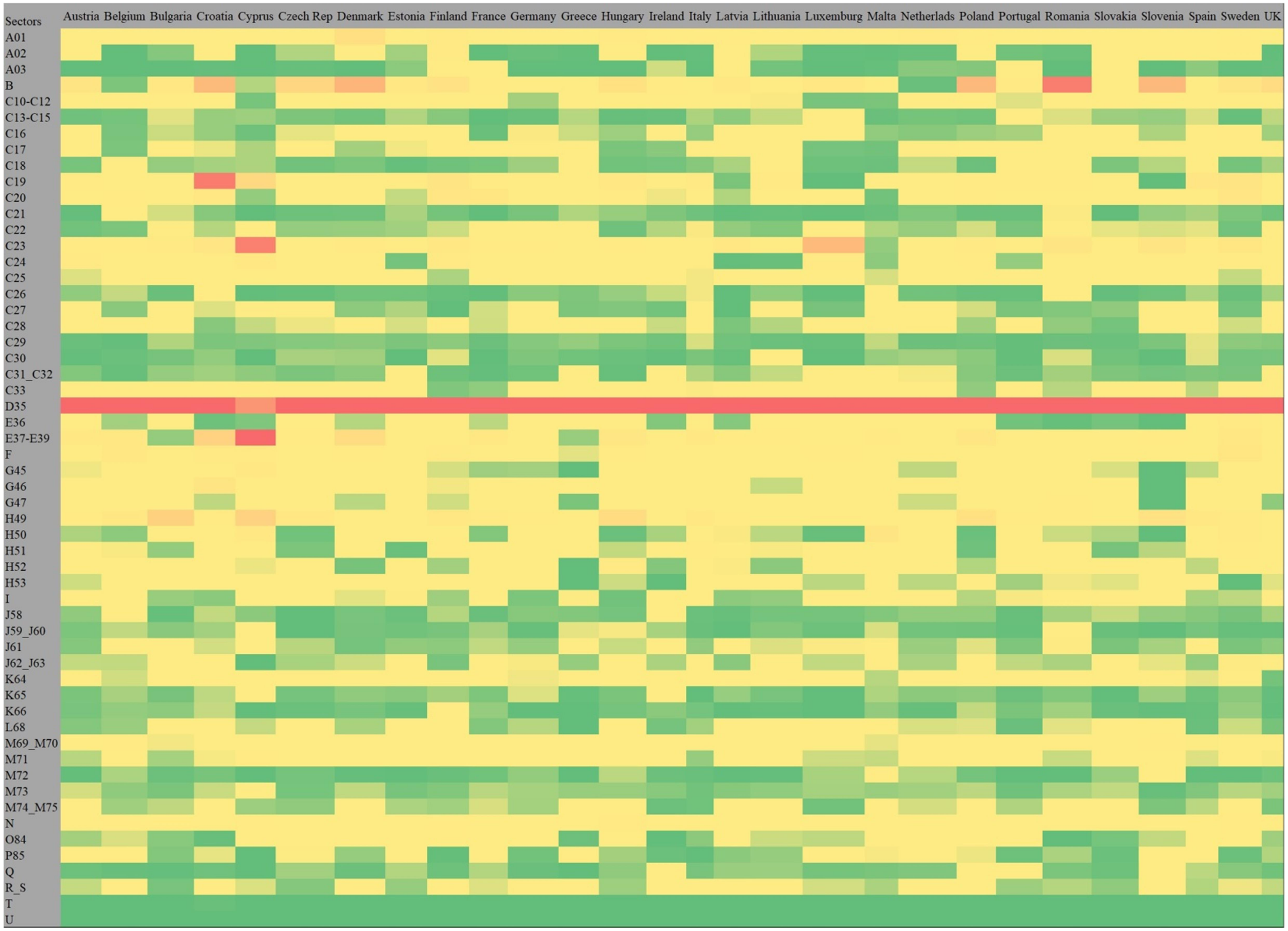


Figure 38A. Thermic tables for GHG contributions by sector for electricity sector – 2014 - direct consumption supply chain

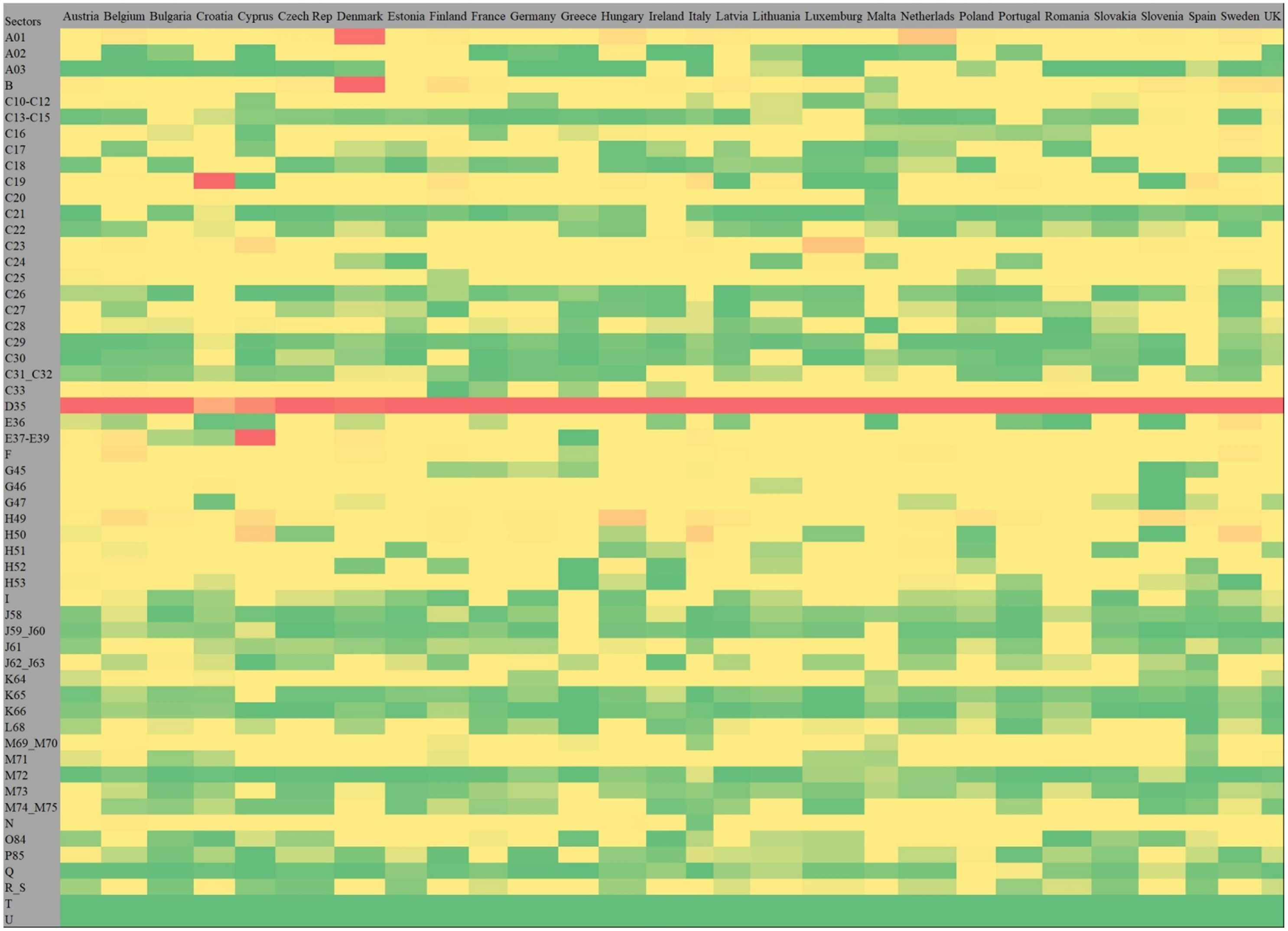


Figure 39A. Thermic tables for ACG contributions by sector for electricity sector – 2010 - direct consumption supply chain

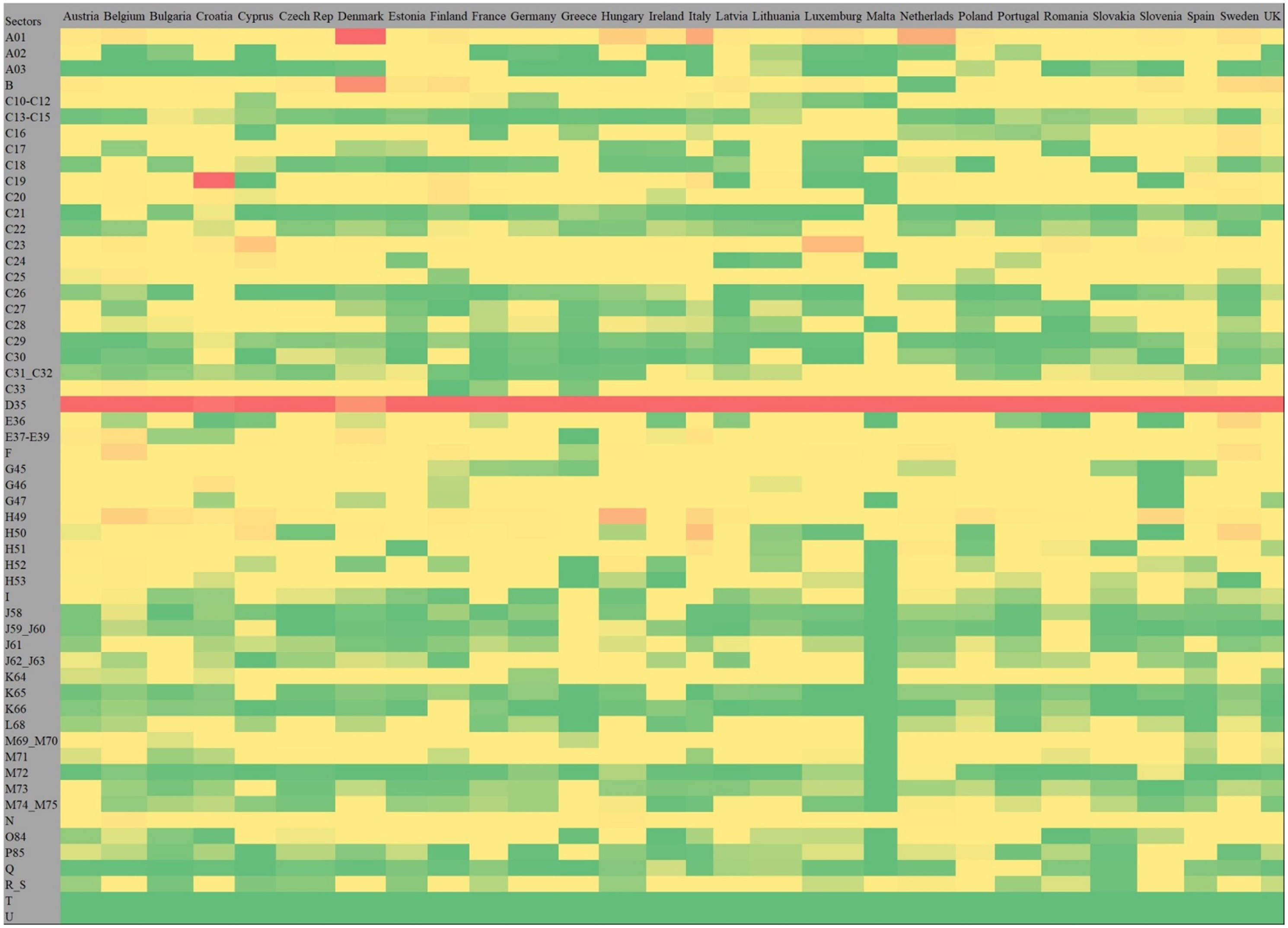


Figure 40A. Thermic tables for ACG contributions by sector for electricity sector – 2014 - direct consumption supply chain

Figure 41A. Thermic tables for O3PR contributions by sector for electricity sector – 2010 - direct consumption supply chain

Figure 42A. Thermic tables for O3PR contributions by sector for electricity sector – 2014 - direct consumption supply chain

APPENDIX 8

Indirect consumption supply chain thermic tables of inputs and outputs contributions by sector for electricity sector.

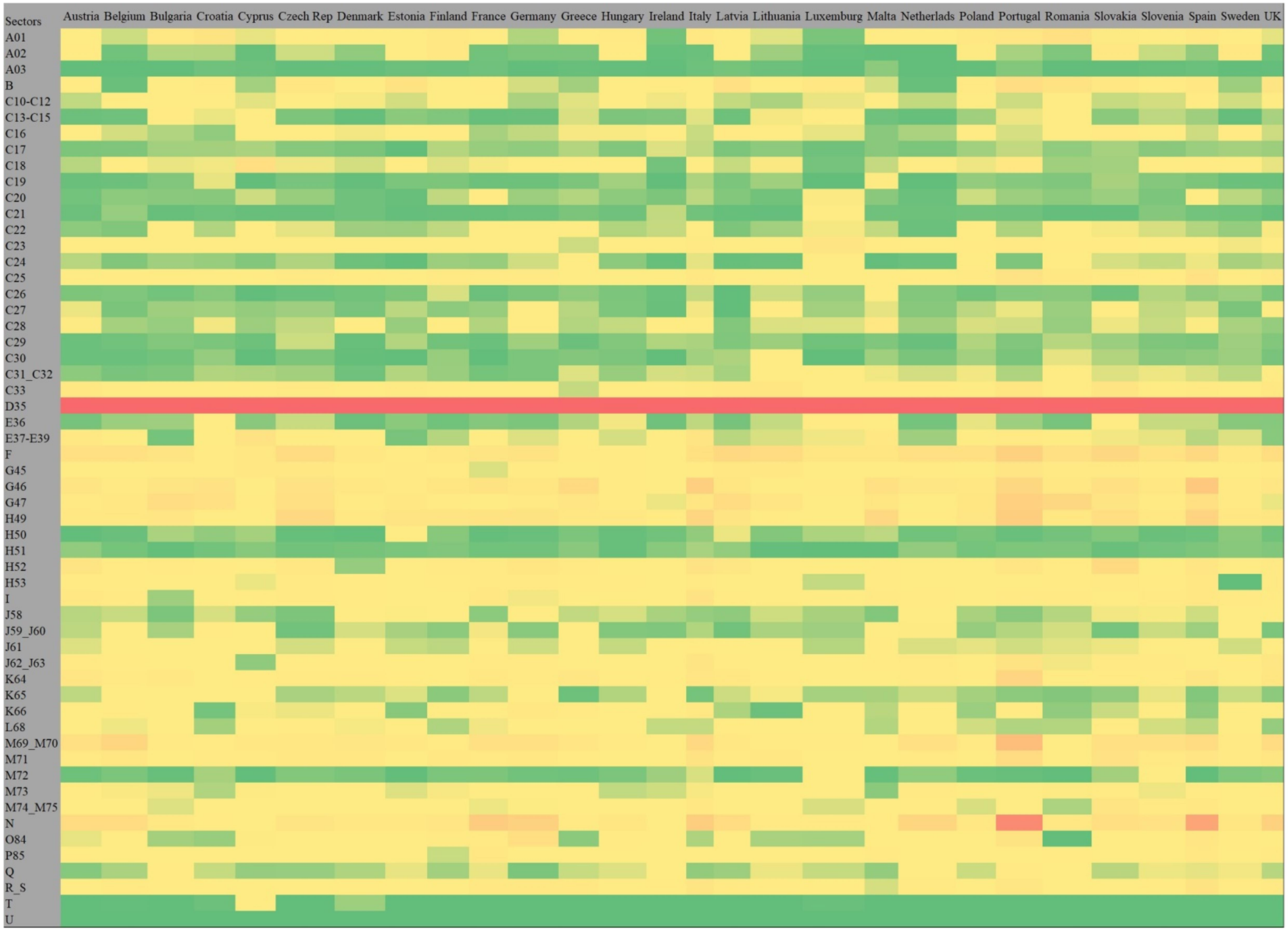


Figure 43A. Thermic tables for Labour contributions by sector for electricity sector - 2010 - indirect consumption supply chain

Figure 44A. Thermic tables for Labour contributions by sector for electricity sector – 2014 - indirect consumption supply chain

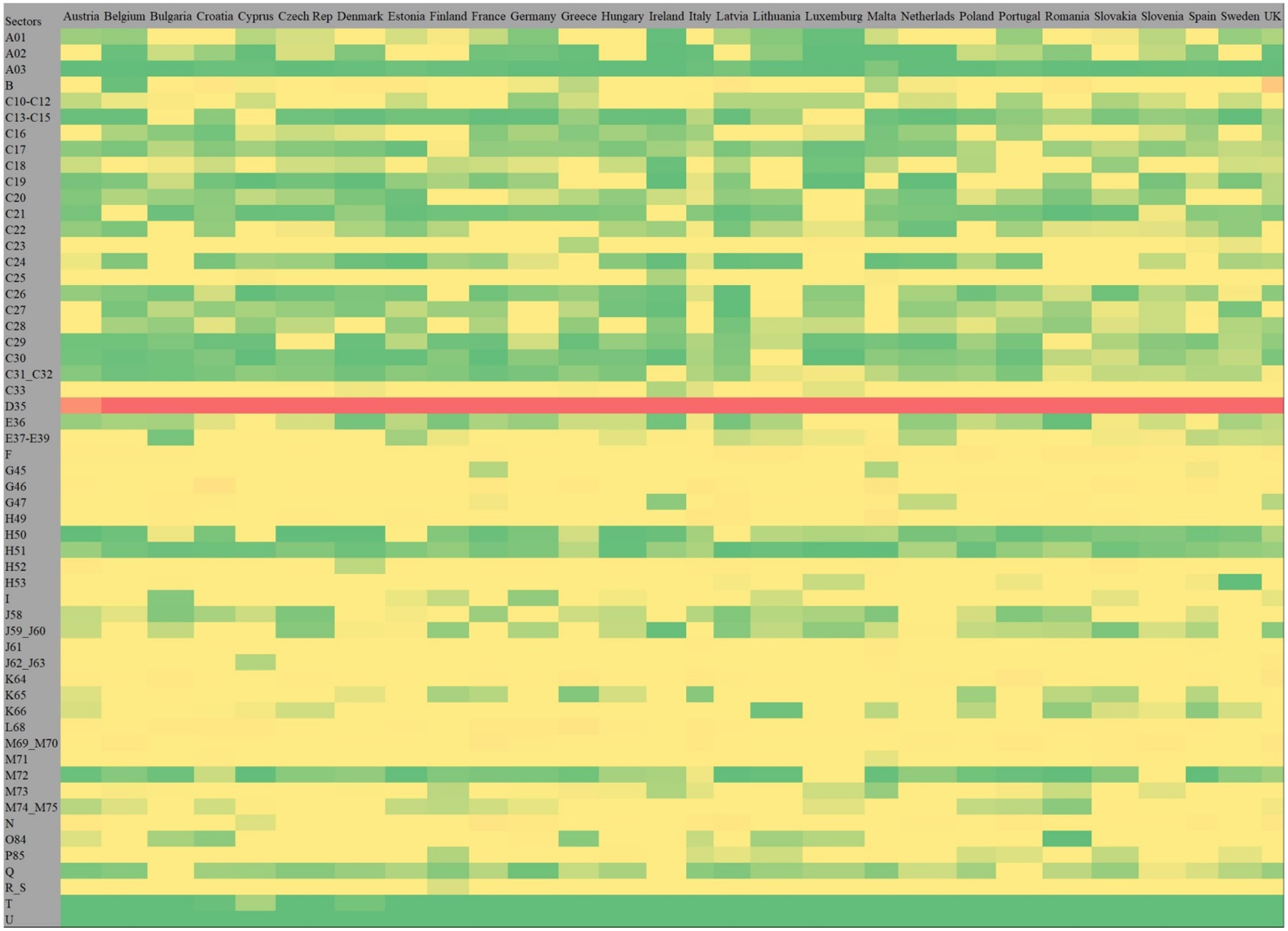


Figure 45A. Thermic tables for GVA contributions by sector for electricity sector – 2010 - indirect consumption supply chain

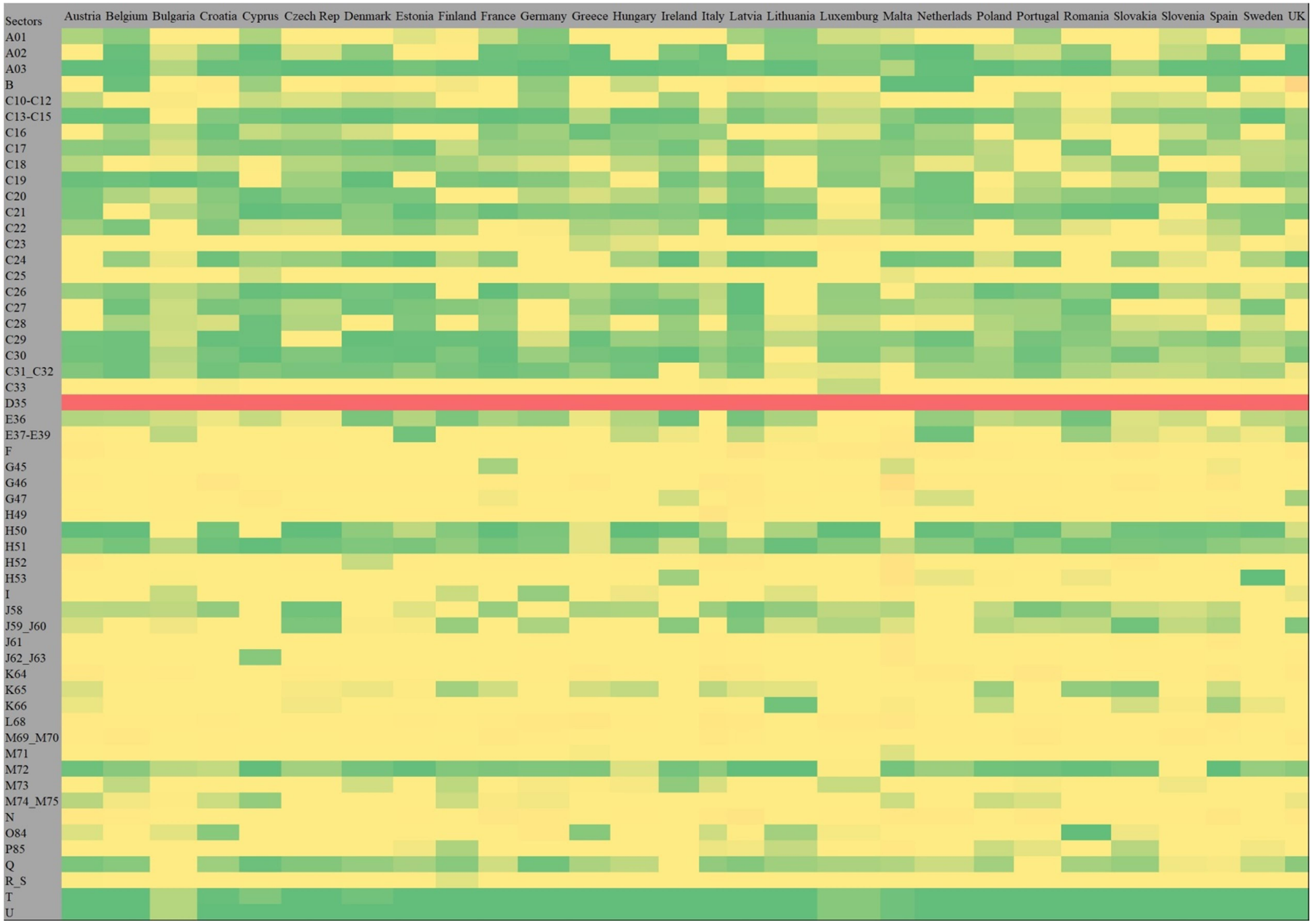


Figure 46A. Thermic tables for GVA contributions by sector for electricity sector – 2014 - indirect consumption supply chain

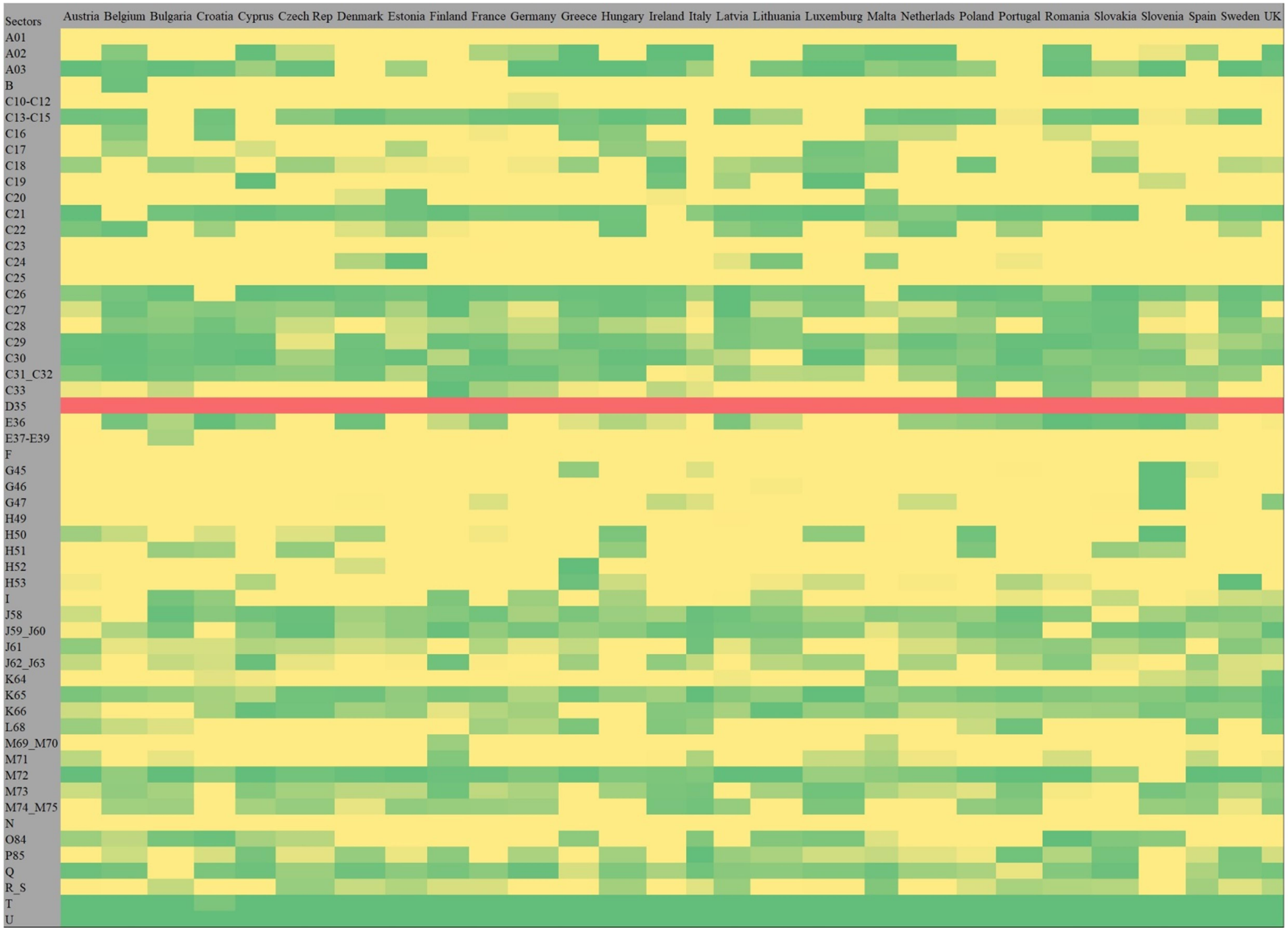


Figure 47A. Thermic tables for GHG contributions by sector for electricity sector – 2010 - indirect consumption supply chain

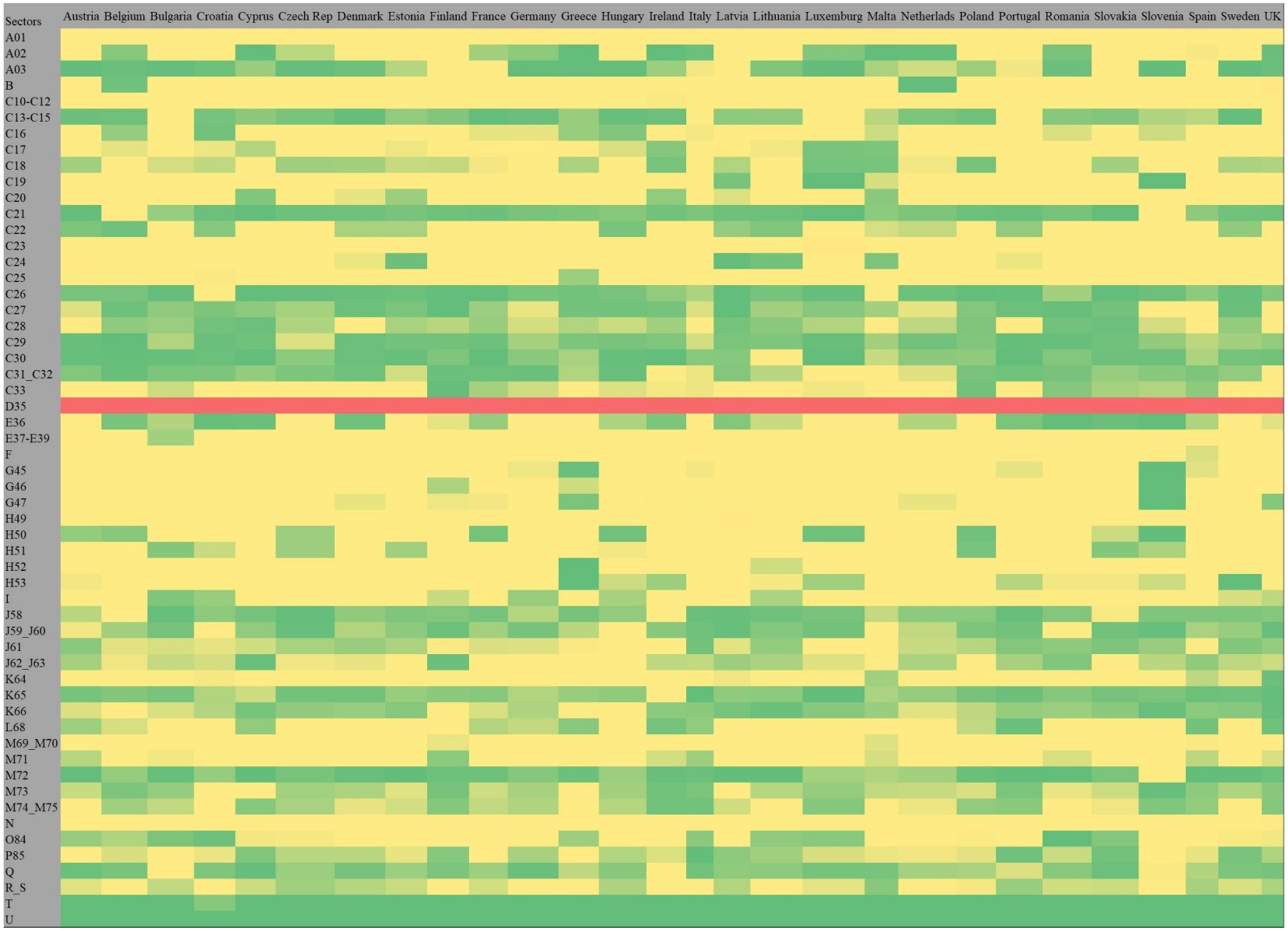


Figure 48A. Thermic tables for GHG contributions by sector for electricity sector – 2014 - indirect consumption supply chain

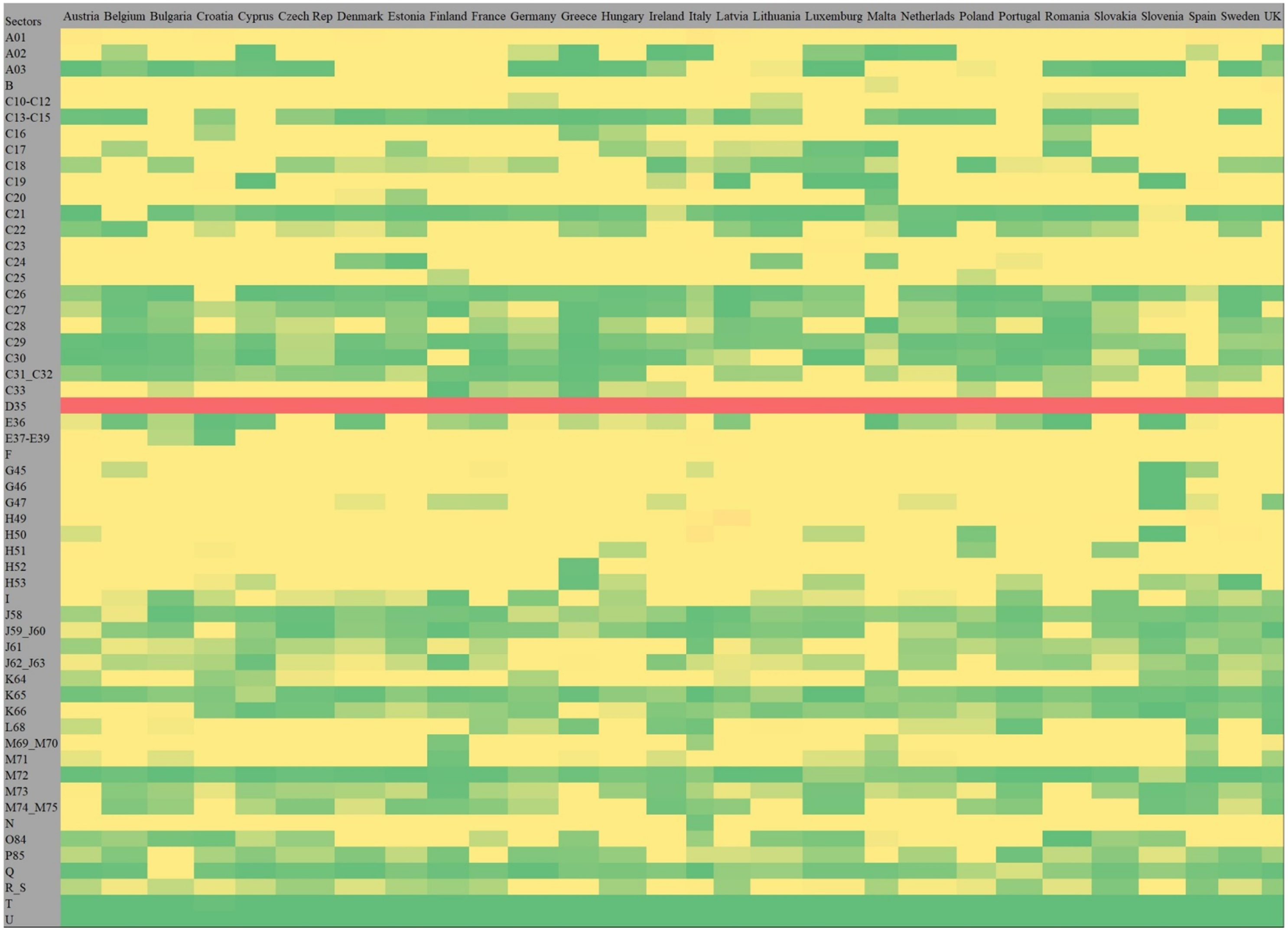


Figure 49A. Thermic tables for ACG contributions by sector for electricity sector – 2010 - indirect consumption supply chain

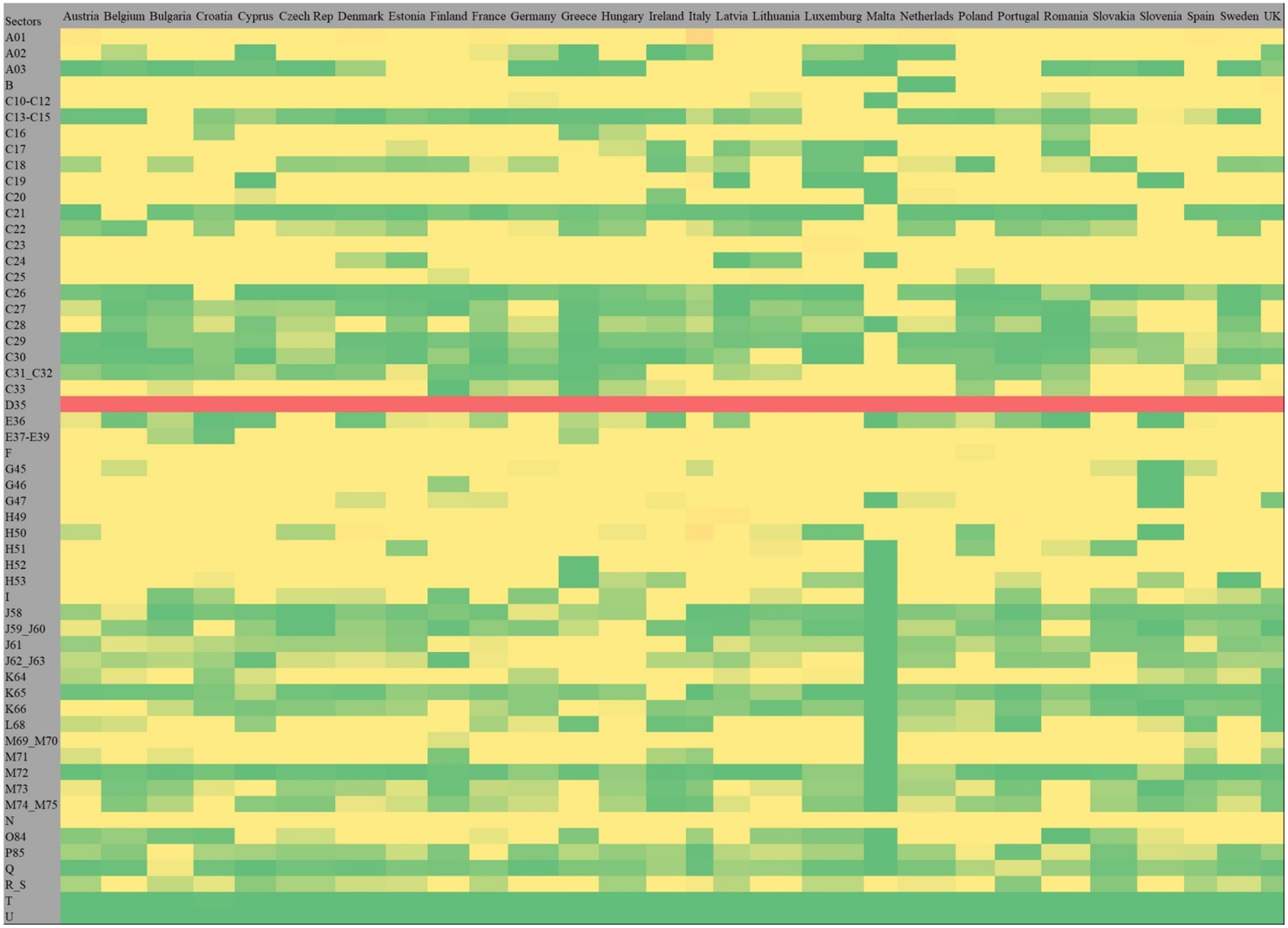


Figure 50A. Thermic tables for ACG contributions by sector for electricity sector – 2014 - indirect consumption supply chain

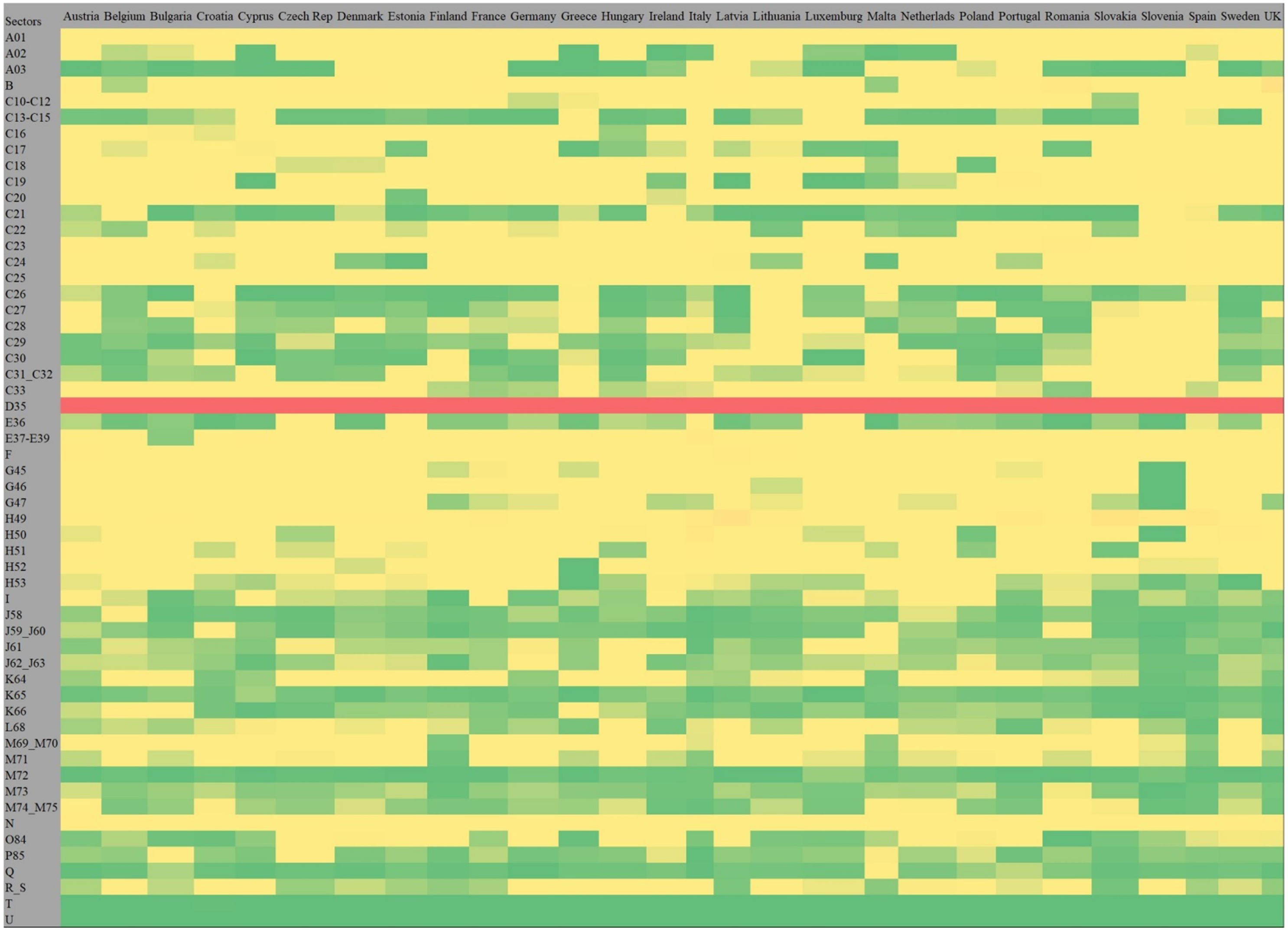


Figure 51A. Thermic tables for O3PR contributions by sector for electricity sector – 2010 - indirect consumption supply chain

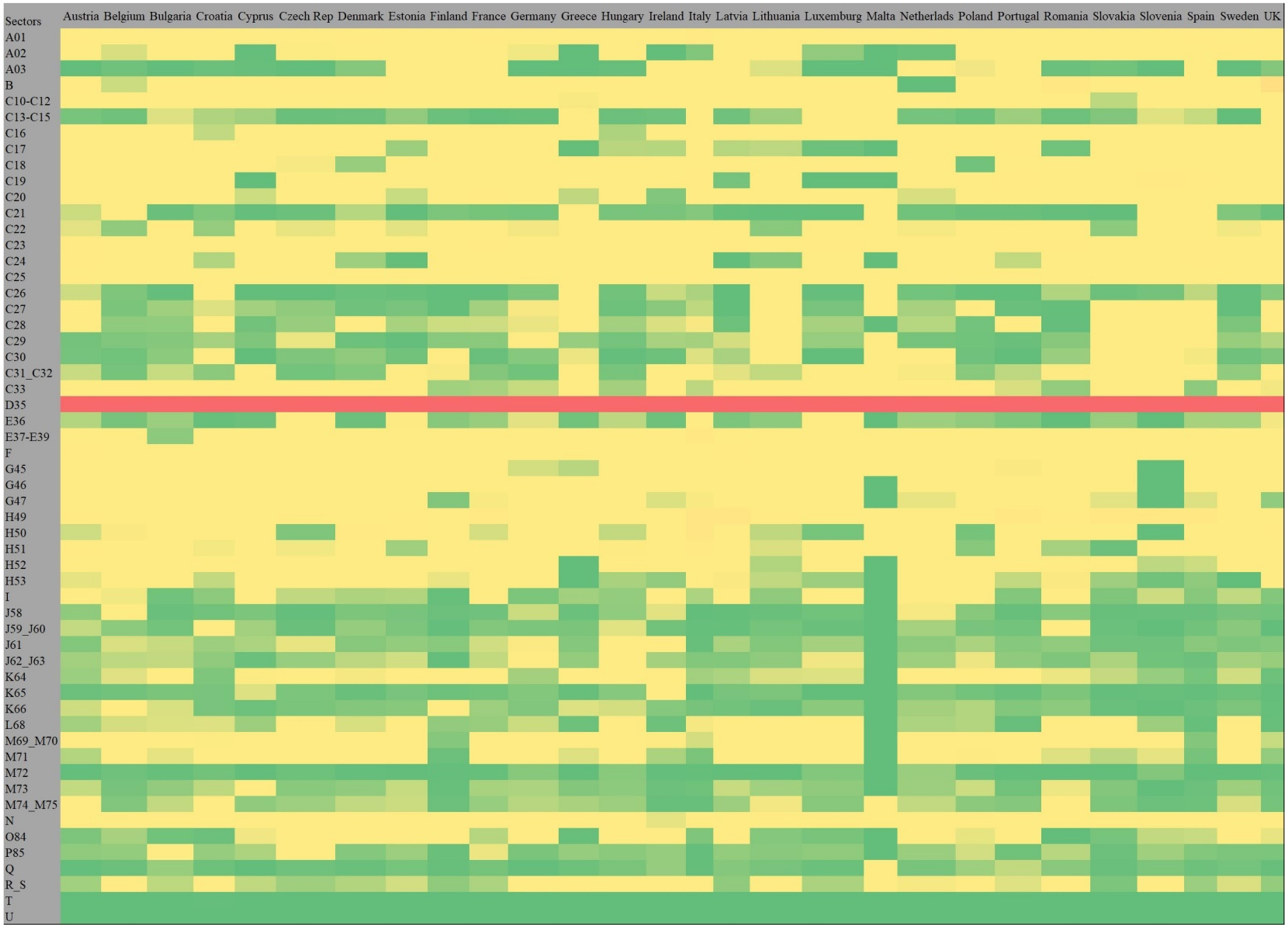


Figure 52A. Thermic tables for O3PR contributions by sector for electricity sector – 2014 - indirect consumption supply chain

APPENDIX 9

Table 1A. Consumption supply chain sector's identification

Sector's identification	
A01 - Crop and animal production, hunting and related service activities	G46 - Wholesale trade, except of motor vehicles and motorcycles
A02 - Forestry and logging	G47 - Retail trade, except of motor vehicles and motorcycles
A03 - Fishing and aquaculture	H49 - Land transport and transport via pipelines
B - Mining and quarrying	H50 - Water transport
C10-C12 - Manufacture of food products, beverages and tobacco products	H51 - Air transport
C13-C15 - Manufacture of textiles, wearing apparel and leather products	H52 - Warehousing and support activities for transportation
C16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	H53 - Postal and courier activities
	I - Accommodation and food service activities
C17 - Manufacture of paper and paper products	J58 - Publishing activities
C18 - Printing and reproduction of recorded media	J59_J60 - Motion picture, video and television program production, sound recording and music publishing activities; programming and broadcasting activities
C19 - Manufacture of coke and refined petroleum products	
C20 - Manufacture of chemicals and chemical products	J61 – Telecommunications
C21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations	J62_J63 - Computer programming, consultancy and related activities; information service activities

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

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