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Abstract
Better management of natural capital, an efficient allocation of resources and technological progress can contribute to productivity change. The present study uses Data Envelopment Analysis to determine the Total Factor Productivity Index, in the case of the EU15 countries, using panel data on energy consumption for a period spanning from 1995 to 2011. The aim is not only to determine the index of total factor productivity change but also to record its driving forces for the decision making units under consideration, showing whether the productivity gains come mainly from an improvement in efficiency or derive merely as a result of technological progress. In terms of eco-efficiency, the paper contributes in showing whether the overall development is more driven by input-saving or environmental-saving processes. The detailed decomposition offers policy makers additional insights into more valuable reference material representing the driving forces of productivity gains or losses.

Keywords: Energy; Energy Consumption; Environmental Economics; Carbon emissions; Eco-Efficiency; Data envelopment analysis; Total factor productivity index.

JEL Codes: O11; O57; Q01; Q40; Q43; Q48; Q50; Q58; R15.

1. Introduction

As reported by Bampatsou *et al*. (2013) the higher share of renewable energy varieties in an energy mix of a country is a necessary but not a sufficient condition for its economic system's sustainability. This is justified by the higher energy demand that cannot be met by relying only on renewable sources. However, the continuation of high energy productivity levels is necessary to guarantee the fulfilment of the energy needs of a country (see Bampatsou *et al*., 2013). In this study we focus on the trend of energy consumption in order to develop a more thoughtful measure of the aspects influencing production efficiency under specific output conditions. Furthermore, bringing together economic and environmental issues, the concept of economic and ecological efficiency, known as eco-(in)efficiency, is utilized.

As indicated by Mahlberg *et al.* (2011) the concept of eco-efficiency claims that it is possible to produce higher levels of goods and services causing less environmental degradation and less consumption of natural resources. As we demonstrate further in this study it is possible for Decision Making Units (henceforth DMUs) to be more efficient or to increase the efficiency and maintain a certain level of environmental performance or to improve both targets simultaneously.

The index of eco inefficiency is a quantity measure in the case of carbon dioxide, which is not priced in most markets. The index incorporates carbon dioxide emissions as undesirable output. Therefore, is not limited to the measurement of productive efficiency for operations involving environmental negative externalities produced by the fossil fuel energy production process (see among others, Chen and Delmas, 2012; Halkos and Polemis, 2016).

The contribution of the paper is twofold: First, by adopting this approach, we are able to identify whether the productivity increase over multiple time periods is a result of an improvement in technical efficiency or a result of technological progress. In this regard, we manage to highlight whether productivity change is more driven by input-saving, environmental-saving or both. Thus, we obtain a useful insight into the way of transforming inputs into outputs. Moreover, the productivity change that may arise from the different composition of the total energy mixture by time is an important topic to be considered.

Second, we apply the Data Envelopment Analysis (DEA) method at a macroeconomic level. This allows us to investigate the performance of the economic systems of the EU15 countries using panel data on energy consumption during 1995-2011. Under these conditions, and following the spirit of the dynamic Malmquist Total Factor Productivity Change (TFPCH) index in the presence of undesirable output, the productivity of energy consumption is measured in order to decompose the TFPCH into two components representing the changes of eco-technical and eco-efficiency respectively.

After a very brief review of the Malmquist productivity index in section 2, the remaining of this paper is organized as follows. Section 3 presents the data set and the empirical methodology. Section 4 contains the empirical results and section 5 discusses the empirical findings in order to have a better understanding of the content of the productivity change from cross-country comparisons. Finally, section 6 concludes with the policy implications.

2. The Malmquist productivity index: A brief history review

Total Factor Productivity (TFP) is a measure of production efficiency and is defined as the index of all outputs divided by all inputs (see, among others Fischer *et al*., 2009; Kitcher *et al*., 2013). The concept of the Total Factor Productivity index was suggested by Malmquist (1953) and its development can be calculated using the Malmquist index. The Malmquist index of TFP growth was developed through a general production function framework by Caves *et al*. (1982).

Malmquist's TFP index can be used to measure the TFPCH of DMUs between two data points by estimating the ratio of distances of each data point in relation to a common technology. The productivity change is determined by the contribution of i) technology innovation (see Sarkis and Weinrach, 2001), ii) productivity improvement (see Bevilacqua and Braglia, 2002), and iii) optimal allocation of resources (see Kuo *et al*., 2010; Fukuyama *et al*., 2013).

The calculation of the TFP index can be obtained using both parametric and non-parametric approaches (see Fried *et al*., 2008). In parametric approaches, the distance functions are determined by parametric methods and, for this reason, the production frontier is a stochastic frontier. In non-parametric approaches, like the one utilized in the present study, the Malmquist Index can be obtained through DEA. The most popular non-parametric approaches used for calculating the distance functions are the linear programming models developed by Färe *et al*., (1994b).

The relevant literature has used the DEA based Malmquist Productivity Index to calculate the performance of different DMUs over time, in the presence of undesirable outputs (see among others, Kortelainen, 2008; Mahlberg *et al*., 2011; Apergis *et al*., 2015; Long *et al.*, 2015). More recently, Makridou *et al.* (2015) suggest an overall energy efficiency and composite performance indicator combining DEA and Multiple Criteria Decision Aiding Methodology (MCDA). Wang and Wei (2016) utilize the Luenberger productivity index, which is also used to calculate productivity change and its components, to analyze energy input-specific and environmental productivity change in China.

As indicated by Murillo-Zamorano (2005) the consideration of technical efficiency contributes to a better understanding of both the temporal evolution and cross-country variability of aggregated productivity growth. However, the research on the driving forces of productivity gains or losses in energy sector and in terms of energy efficiency and CO_2 emission performance appears very limited at microeconomic level with more representative contribution from Martínez (2013). To the best of our knowledge there is no research addressing the issue at macroeconomic level using the input-specific Malmquist productivity index. Therefore, the present paper aims to fill in this gap in order to help DMUs to evaluate economic policies more effectively.

Moreover, the current research aims to assist policymakers in improving the eco-efficiency of economic growth with less resource consumption and lower pollution through new technologies and more effective management of energy resources.

3. Data and methodology

DEA is used here to determine the TFP (Malmquist) Index. For this purpose panel data on energy consumption of the EU15[1] countries are utilized. The time period spans from 1995 to 2011 (i.e. *T=15; N=17*). To determine the Malmquist index, the entire EU15 is considered as a separate entity and each of the individual EU15 countries is

[1] Due to data availability we have based our analysis on the EU-15.

taken as different DMU. Estimates are based on an input oriented DEA model. The index of the Total Primary Energy Consumption per capita is used as input[2], while GDP per capita and CO_2 emissions per capita from the consumption of energy are used as desirable and undesirable outputs respectively.

A necessary point concerning the choice of inputs and outputs is that they are not specified following the restrictions of the traditional DEA (Halkos and Salamouris, 2004). In the context of the current application, GDP and CO_2 emissions[3] are not the outputs solely due to fossil and non-fossil energy consumption but the representative outputs and inputs relevant to the calculation of the DEA-based Malmquist productivity index. Compared to other methods and as noted by Fagerberg (1994), TFP evaluates the contribution of technology progress and economies of scale to economic growth without the effect of land, capital, labor and other traditional elements. An analogous macroeconomic context of DEA applications (cross section/panel data analysis) has been described in the literature (see, among others, Golany and Thore, 1997; Ramanathan, 2006; Bampatsou and Hadjiconstantinou, 2009; Bampatsou *et al.*, 2013; Xishuang *et al.*, 2014; Sheng *et al.*, 2015). More recently, Sueyoshi, and Yuan, (2016), suggest a new approach on energy and sustainability as they measure the degree on Marginal Rate of Transformation and Marginal Rate of Substitution through DEA environmental assessment.

[2] Although a production function requires the use of L and K our intention is to see the direct effect of energy on both desirable and undesirable outputs.

[3] For more information on CO_2 and in general GHG emissions and the associated problems see among others Halkos (2010, 2014), Halkos and Tsilika (2014, 2016), Halkos and Skouloudis (2016).

3.1. Data sources and Definitions

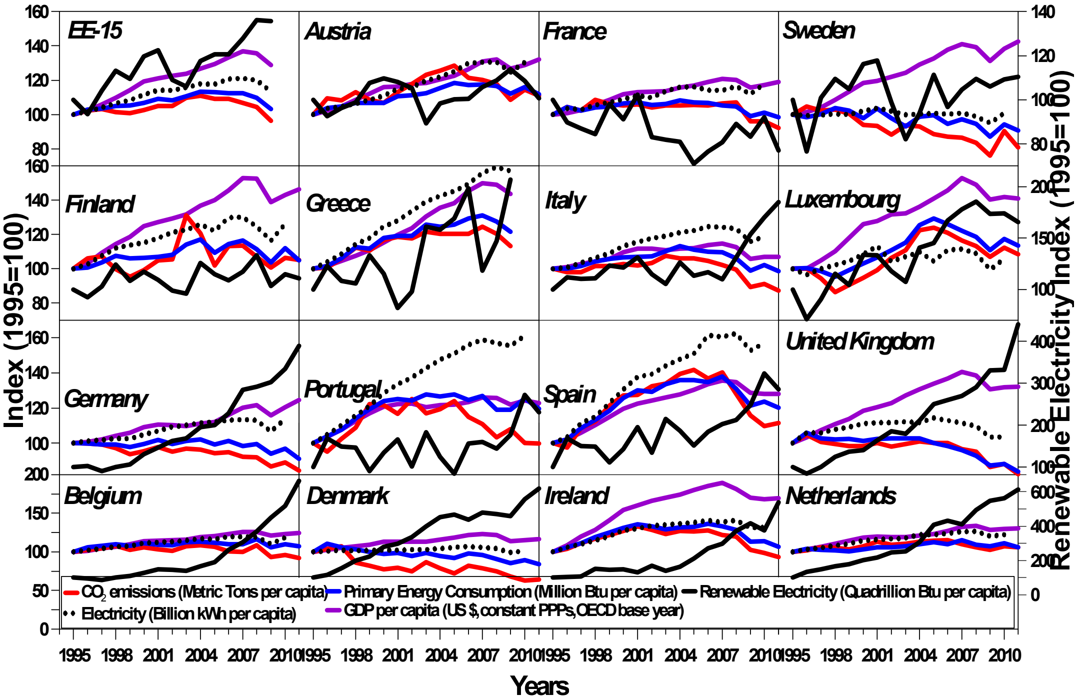
For each country, the total primary energy consumption indicates the energy that has not been subjected to any conversion or transformation process. Total primary energy consumption includes the consumption of petroleum, dry natural gas, coal, and net nuclear, hydroelectric and non-hydroelectric renewable electricity. It also includes net electricity imports (imports minus exports).

CO_2 emissions from the consumption of energy include emissions due to the consumption of petroleum, natural gas, and coal, and also from natural gas flaring. Our study focuses on CO_2 because is by far the largest contributor to the greenhouse effect.

The data set is presented in a summarized form in Figure 1. All energy data comes from EIA (2013) while all GDP data comes from OECD (2013). The left-hand side vertical axis represents CO_2 emissions, Total Primary Energy Consumption, GDP and Electricity Net Consumption while the right-hand side vertical axis represents Renewable Electricity Net Consumption (all expressed per capita).

As input we use the total energy consumption, composed of renewable and exhaustible energy resources. The input is in this case responsible for the simultaneous production of both desirable product (GDP), which typically has a positive price, and non marketed undesirable byproduct (CO_2 emissions). The fact that desirable and undesirable outputs are jointly produced or null-jointly produced indicates, in the terminology of Shephard and Färe (1974), that the production of desirable outputs is not possible without the production of undesirable outputs.

Figure 1: Development trends of inputs and outputs for the entire EU15 and for each of the individual EU15 countries (EIA, 2013; OECD, 2013)



The use of the Malmquist input-oriented productivity index (TFPCH) makes possible to decompose the productivity changes into technical change index (TECHCH) and technical efficiency change index (EFFCH). These two indexes indicate which factors drive the change of energy efficiency and the magnitude of this change.

3.2 The model

Following Färe *et al.* (1994a), the input oriented Malmquist productivity change index may be formulated as shown in [1] for an assessment involving inputs and outputs:

$$M_I^{t+1}(y^{t+1},x^{t+1},y^t,x^t)=\left[\frac{D_I^t(y^{t+1},x^{t+1})}{D_I^t(y^t,x^t)}\times\frac{D_I^{t+1}(y^{t+1},x^{t+1})}{D_I^{t+1}(y^t,x^t)}\right]^{1/2} \qquad (1)$$

where I indicates an input-orientation, y denotes output, x denotes input, M is the productivity of the most recent production point relative to the earlier production point, and D denotes the input distance function.

The first ratio inside the brackets stands for the Malmquist index for period t. It shows the previous production point (x^t, y^t), using period t technology. It calculates productivity change from period t to period $t+1$ using the technology level at period t as a benchmark. With the input Malmquist Productivity Index relying on technology of period t we have:

$$M_I^t = \frac{D_I^t(y^{t+1}, x^{t+1})}{D_I^t(y^t, x^t)} \quad (2)$$

Similarly, the second ratio inside the brackets corresponds to the Malmquist index for period $t+1$. It specifies the most recent production point (x^{t+1}, y^{t+1}) using period $t+1$ technology. It computes the change in productivity from period t to period $t+1$ using the technology level at period $t+1$ as a benchmark. With input Malmquist Productivity Index being based on the technology of period $t+1$ we have:

$$M_I^{t+1} = \frac{D_I^{t+1}(y^{t+1}, x^{t+1})}{D_I^{t+1}(y^t, x^t)} \quad (3)$$

We may also present the Malmquist Productivity Index in a similar form as shown in [4].

$$M_I^{t+1}(y^{t+1}, x^{t+1}, y^t, x^t) = \frac{D_I^{t+1}(y^{t+1}, x^{t+1})}{D_I^t(y^t, x^t)} \left[\frac{D_I^t(y^{t+1}, x^{t+1})}{D_I^{t+1}(y^{t+1}, x^{t+1})} \times \frac{D_I^t(y^t, x^t)}{D_I^{t+1}(y^t, x^t)} \right]^{1/2} \quad (4)$$

or $$M_I^{t+1}(y^{t+1}, x^{t+1}, y^t, x^t) = \underbrace{\frac{D_I^{t+1}(y^{t+1}, x^{t+1})}{D_I^t(y^t, x^t)}}_{EFFCH} \underbrace{\left[\frac{D_I^t(y^{t+1}, x^{t+1})}{D_I^{t+1}(y^{t+1}, x^{t+1})} \times \frac{D_I^t(y^t, x^t)}{D_I^{t+1}(y^t, x^t)} \right]^{1/2}}_{TECHCH} \quad (5)$$

The ratio outside the brackets in equation [5] is defined as the technical efficiency change index (EFFCH) and the ratios inside the brackets as the technical change index (TECHCH). Therefore, the Malmquist total factor productivity index is the product of an efficiency change over the same period and a measure of technical progress as calculated by shifts in the frontier measured at periods $t + 1$ and t.

The Malmquist Index values and its components may be greater, equal or smaller than 1. Hence, it is easy to understand that we have the following three cases:

(i) If Malmqusit Productivity Index between time periods t and t+1 is greater than 1, then there is an improvement in energy consumption performance

(ii) If Malmquist Productivity Index is equal to 1, then energy consumption performance remains unchanged, and

(iii) If Malmquist Productivity Index is smaller than 1, then energy consumption performance declines.

The decomposition of Malmquist Productivity Index into two components (EFFCH and TECHCH) helps to identify the reasons for the change of the energy consumption performance.

Changes in efficiency (EFFCH) between time periods t and $t+1$ are usually interpreted as technological catch-up, as they measure the change of the energy consumption performance in the reference periods and therefore how much a country approaches the production frontier. On the other hand, changes in technology (TECHCH) are viewed as the result of innovation efforts as noted by Färe *et al.* (1994b), or investment in intangibles as noted by Corrado *et al.* (2009).

Corrado *et al.* (2005), argue that intangible assets can be described as resources utilized in soft investments, related to the creation and control of knowledge and further innovations in energy conservation. Intangible assets have three categories (namely computerized information, innovative property and economic competencies) and ten detailed types of assets (namely software, database, R&D, mineral exploration, copyright and licenses, product development in the financial industry, new architectural and engineering design, brand equity, firm-specific human capital and organizational capital).

The second component (TECHCH) measures the shift of the empirical production frontier between time period t and $t+1$, which indicates the shift in production technology of an economic system based on energy consumption.

As noted by Ramli and Munisamy (2013), the disregard of undesirable outputs in efficiency analysis may produce misleading results. Therefore, it is necessary to examine the effects of undesirable outputs on productivity change over time. In order to measure productivity when both desirable and undesirable outputs are produced, their joint production should be examined, as the production of desirable outputs is possible, only when is accompanied by the simultaneous production of undesirable outputs. Fixler and Ziechang (1992) developed an emission-incorporated Malmquist TFP index and defined their input-oriented productivity index as shown in equation [6], which is an extended form of equation [5] that includes the attribute vector a:

$$M_{\alpha}^{Fixler}(x^{t+1}, y^{t+1}, \alpha^{t+1}, x^{t}, y^{t}, \alpha^{t}) = \left[\frac{D^{t}(x^{t}, y^{t}, \alpha^{t})}{D^{t}(x^{t+1}, y^{t+1}, \alpha^{t+1})} \times \frac{D^{t+1}(x^{t}, y^{t}, \alpha^{t})}{D^{t+1}(x^{t+1}, y^{t+1}, \alpha^{t+1})} \right]^{1/2} \tag{6}$$

The definition of Färe *et al.* (1995) is actually a reciprocal of the Fixler and Ziechang's (1992) one. Färe *et al.* (1995) proposed a new Malmquist index to incorporate the non-marketable attributes of production. The aim of using this approach is to calculate the energy consumption efficiency and the degree of input reduction to reach the empirical production frontier. The following model can be used to measure the performance in a time period and the distance function can also be calculated, incorporating undesirable output.

$$M_{\alpha}^{Fare}(x^{t+1}, y^{t+1}, \alpha^{t+1}, x^{t}, y^{t}, \alpha^{t}) = \left[\frac{D^{t}(x^{t+1}, y^{t+1}, \alpha^{t+1})}{D^{t}(x^{t}, y^{t}, \alpha^{t})} \times \frac{D^{t+1}(x^{t+1}, y^{t+1}, \alpha^{t+1})}{D^{t+1}(x^{t}, y^{t}, \alpha^{t})} \right]^{1/2} \quad (7)$$

Based on the same logic as in equation [5], equation [7] can be decomposed into two factors. These are:

$$M_{\alpha}^{Fare} = \underbrace{\frac{D^{t+1}(x^{t+1}, y^{t+1}, \alpha^{t+1})}{D^{t}(x^{t}, y^{t}, \alpha^{t})}}_{\text{EFFCH}_{\alpha}} \underbrace{\left[\frac{D^{t}(x^{t+1}, y^{t+1}, \alpha^{t+1})}{D^{t+1}(x^{t+1}, y^{t+1}, \alpha^{t+1})} \times \frac{D^{t}(x^{t}, y^{t}, \alpha^{t})}{D^{t+1}(x^{t}, y^{t}, \alpha^{t})} \right]^{1/2}}_{\text{TECHCH}_{\alpha}} \quad (8)$$

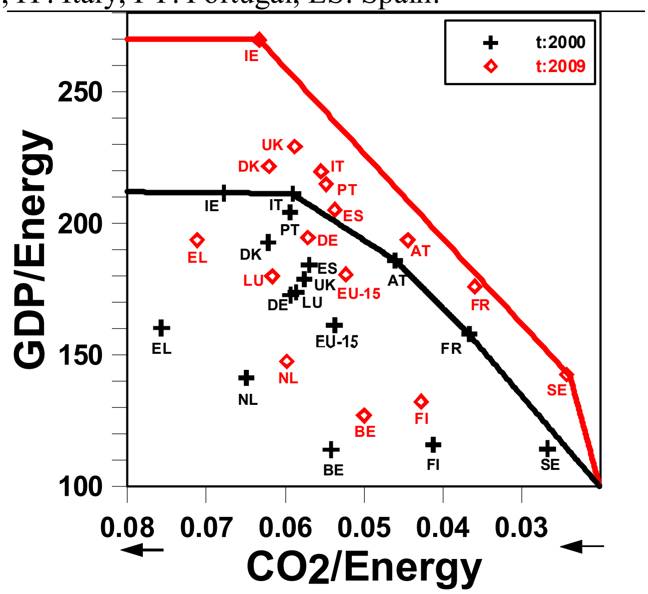
As noted by Charnes *et al*. (1993), the productivity gains are mainly the result of an improvement in efficiency if EFFCH>TECHCH and mainly the result of technological progress if EFFCH<TECHCH

As formalized by Färe and Lovell (1978), the input-oriented efficiency measure of Farrell (1957) is the same as the inverse of Shephard's (1970) input distance function, which provides the theoretical basis of the current study for the calculation of the Malmquist production index by considering energy consumption. Therefore, values greater than one of the input oriented version of the Malmquist index indicate an improvement.

4. Empirical results

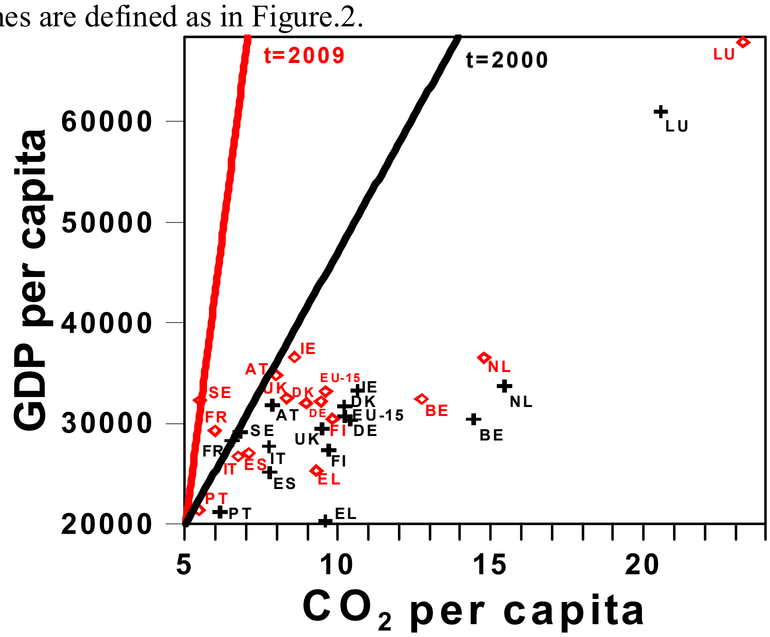
First, we obtain the production possibility frontier (PPF), presented in Figure 2. The PPF indicates the points with the maximum possible desirable output and the minimum amount of emissions that can be produced from a DMU, using the available technology. The horizontal axis represents the undesirable byproduct (CO_2 emissions) and the vertical axis represents the desirable output (GDP). The output quantity of each DMU is divided by its input quantity in order to evaluate the DMUs' eco-inefficiency based on GDP and CO_2 emissions. In this case, the PPF is the locus of all potentially technically efficient input-output combinations. Therefore, here, technical efficiency refers to the ability to use a minimal amount of input to produce a given level of total output. This is displayed in the forms of desirable GDP and undesirable CO_2 emissions.

Figure 2: Input-saving productivity change from 2000 to 2009. FR: France, DE: Germany, IE: Ireland, LU: Luxembourg, NL: Netherlands, SE: Sweden, UK: United Kingdom, AT: Austria, BE: Belgium, DK: Denmark, FI: Finland, EL: Greece, IT: Italy, PT: Portugal, ES: Spain.



As a next step to our analysis, we obtain Figure 3, which shows the relationship between GDP production per capita and CO_2 emissions per capita for the EU15 countries under examination. From this figure the efficiency frontiers are obtained by connecting the origin with the furthest point to the left. Under the assumption of constant returns to scale and as noted by Chames *et al.* (1978), the efficiency frontier is defined by a straight line starting from the beginning of the axes (which determine the production function) and passing through the point of the unit with the highest ratio of outputs to inputs.

Figure 3: Environmental saving-productivity change from 2000 to 2009. The country names are defined as in Figure.2.



The distance function now measures the maximal proportional change in outputs required to make the production point at $t+1$ (x^{t+1}, y^{t+1}, α^{t+1}) feasible in relation to the technology at t (Figure 3). From Figure 3 it can be seen that production point at $t+1$ (x^{t+1}, y^{t+1}, α^{t+1}) occurs outside the set of feasible production in period t indicating the occurrence of technological progress (see for example the observation for France – denoted by FR – in 2009). Similarly, one may define a distance function that measures the maximal proportional change to output required to make the production point at t (x^t, y^t, α^t) feasible in relation to the technology at $t+1$.

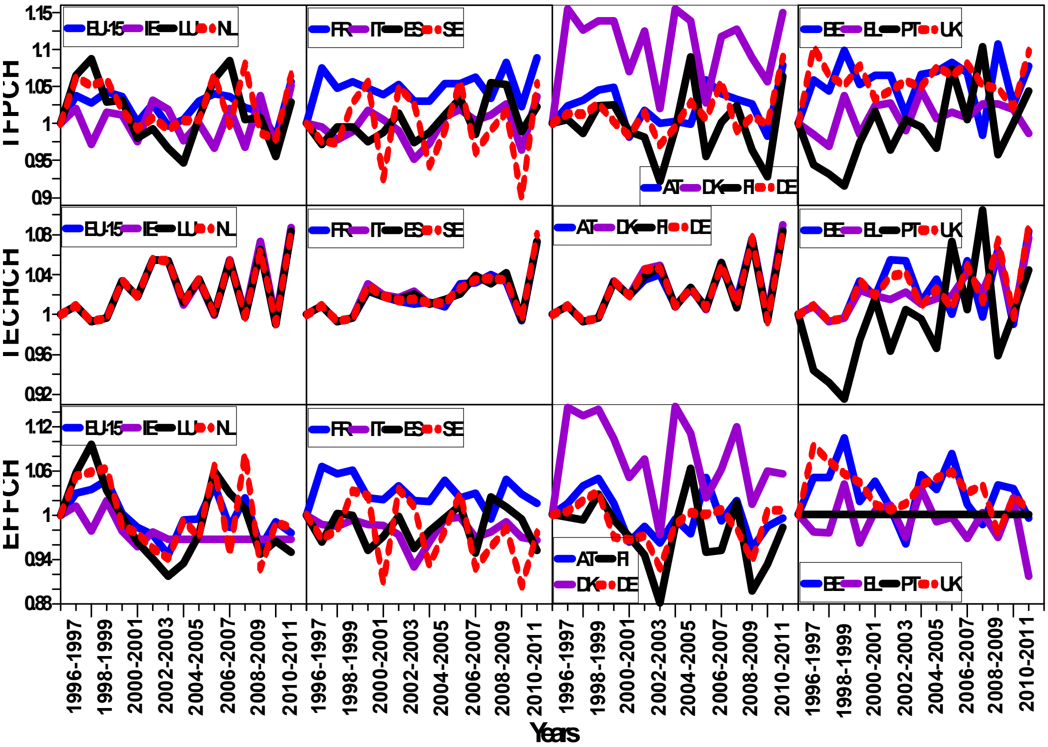
Combining the results of production possibility frontiers depicted in Figure 2 and Figure 3, one can see whether the overall development is driven by environmental-saving or input-saving factors.

If inefficiency is ignored, it is impossible to explain further the relative movement of any given DMU over time. Therefore, productivity growth over time will be unable to distinguish between improvements deriving from a DMU 'catching up' to its own frontier, or those resulting from the overtime shifting up of the frontier itself. This indicates that in the absence of inefficiency, there is no way of distinguishing the position of the DMU relative to the corresponding frontier (eco-efficiency regress) and the position of the frontier itself (technical progress).

On the other hand, when inefficiency is assumed to exist, the relative movement of any given DMU over time will depend on both its position relative to the corresponding frontier (technical efficiency) (Figure 2) and the position of the frontier itself (technical change) (Figure 3).

However, from Figures 2 and 3 still remains unclear which one of these phenomena (eco-technical progress or eco-efficiency regress) is predominant, and, therefore, whether total factor productivity increases or decreases. In order to answer this question, the Malmquist index (TFPCH) needs to be calculated and decomposed into efficiency change (EFFCH) and technical change (TECHCH). This is presented graphically in Figure 4.

Figure 4: Cumulative index of TFPCH, TECHCH, EFFCH (Index: 1995=1). The country names are defined as in Figure 2.



Detailed observations of Figure 4 are included in Table 1. Table 1 reports for each country and each year, when productivity gains are a result of an improvement in efficiency or not; and also, when there is a technological progress/loss and a productivity progress/loss. Table 1 is constructed through a step-by-step procedure until the final results are obtained. The procedure is as follows:

The first step is to determine the difference between the two indexes of TECHCH and EFFCH. As it was mentioned before, productivity change is mainly derived from an improvement in efficiency (EFF) (this occurs when TECHCH-EFFCH<0). Also, productivity change is mainly the result of technological progress (TECH) (when TECHCH-EFFCH>0). If there is no difference between TECHCH and EFFCH, the improvement in efficiency is the same to technological progress (EFF=TECH).

During the period under consideration, the difference between the two indexes of TECHCH and EFFCH for the entire EU15 and for each of the individual EU15 countries can be negative, positive or zero (see Table A1 in the Appendix).

From the obtained results we observe that the frequency of occurrence of negative value (TECHCH-EFFCH<0) is: *twelve times* in the case of Denmark, *ten times* in the case of France, *nine times* in the case of the United Kingdom, *eight times* in the case of Portugal, *seven times* in the case of Belgium, *five times* in the cases of the entire EU15, Luxembourg, Netherlands and Austria, *three times* in the cases of Sweden, Finland, Germany and Greece, *two times* in the cases of Ireland and Spain and *zero times* in the case of Italy.

In this case (negative difference between the two indexes of TECHCH and EFFCH) the productivity change is mainly derived from an improvement in efficiency (EFF).

DMUs with an incidence of at least 7 times negative value (TECHCH-EFFCH<0), show a negative average (France: -0.014, Denmark: -0.054, Belgium: -0.006, Portugal: -0.007, United Kingdom:-0.009). Therefore, these countries have mainly invested in methods to improve efficiency, through appropriate energy policies and regulations.

The frequency of occurrence of positive value (TECHCH-EFFCH>0) is: *fifteen times* in the case of Italy, *thirteen times* in the cases of Ireland and Spain, *twelve times* in the cases of Sweden, Germany and Greece, *eleven times* in the case of Finland, *ten times* in the cases of Luxembourg, Netherlands and Austria, *eight times* in the case of Belgium, *nine times* in the case of the entire EU15, *six times* in the cases of Portugal and the United Kingdom, *four times* in the case of France and *three times* in the case of Denmark

In this case (positive difference between the two indexes of TECHCH and EFFCH) the productivity change is mainly the result of technological progress (TECH).

DMUs with an incidence of at least 9 times positive value (TECHCH-EFFCH>0), show a positive average (the entire EU-15: 0.0285, Ireland: 0.0523, Luxembourg: 0.0353, Netherlands: 0.0276, Italy: 0.0429, Spain: 0.0365, Sweden: 0.0438, Austria: 0.0263, Finland: 0.0535, Germany: 0.0387, Greece: 0.0319). Therefore, these countries have mainly invested in methods to improve technology, through appropriate energy policies and regulations.

The frequency of occurrence of zero value (TECHCH=EFFCH) is: one time in the cases of the entire EU15, France, Finland and Portugal. In this case (no difference between the two indexes of TECHCH and EFFCH) the productivity change is the result of both technological progress (TECH) and efficiency improvement (EFF).

At this point it should be noted that, for all EU-15 countries except Italy, the values (TECHCH-EFFCH) in different spans of time are alternating between positive and negative ones. When the time span with a homogenous pattern (numbers with the same sign) is long, then there is a short-term effort for energy policy stabilization in one direction, geared towards an improvement in efficiency (EFF) or towards a technological progress (TECH). In that respect, alternation exists when a policy is not performing as expected. When the time span with a homogenous pattern (numbers with the same sign) is short (one or two years), then there is a mild policy without clear orientation towards one direction (an improvement in efficiency) or another (technological progress).

The main objective of the energy strategy and policy is to provide a short-term plan for rehabilitation of the energy sector. Furthermore, it gives the directions for the medium to long-term reconstruction of the energy sector. The energy strategy shows how DMUs can use their energy resources to achieve economic and social benefits in an environmentally responsible manner. It gives the directions and the objectives of comprehensive and inclusive policy geared towards an improvement in efficiency (EFF) or towards a technological progress (TECH) or towards a combination of the two.

The second step of our analysis is to see if the Malmquist Productivity Index between two periods t and t+1 is greater than 1, smaller than 1 or remains unchanged in the case of the entire EU15 and for each individual EU15 country (see Table A2 in the Appendix).

In terms of productivity change from one year to the next and under constant returns to scale, an improvement of productivity can be the result of a single factor, or a combination of two factors known as technical change (technological progress) and efficiency change (improvement in efficiency). For example, one DMU may increase its productivity solely by technical change and with no change of the distance to the respective frontier. In other cases, the productivity change is a combination of technical change and technical efficiency change. To summarize, productivity change can be a result of technical change, technical efficiency change or a combination of the two.

During the period under consideration, the total factor productivity index (see Table A2 in the Appendix) for the entire EU15 and for each of the individual EU15 countries can be greater or smaller than one. The frequency of occurrence of total factor productivity index with values greater/smaller than one (TFPCH>1/ TFPCH<1), is:

- in the case of entire EU15, TFPCH index is 13 (2) times greater (smaller) than one
- in the case of Ireland, TFPCH index is 9 (6) times greater (smaller) than one
- in the cases of Luxembourg, Netherlands, Germany and Greece, TFPCH index is 10 (5) times greater (smaller) than one
- in the cases of France, Denmark and the United Kingdom, TFPCH index is 15 times greater than one (the whole sample period)
- in the case of Italy, index of TFPCH is 8 (7) times greater (smaller) than one
- in the case of Spain, the index of TFPCH is 6 (9) times greater (smaller) than one
- in the cases of Sweden , Finland and Portugal, the index of TFPCH is 7 (8) times greater (smaller) than one
- in the case of Austria, the index of TFPCH is 12 (3) times greater (smaller) than one
- in the case of Belgium, the index of TFPCH is 14 (1) times greater (smaller) than one

It should be mentioned that in the case where the total factor productivity index between time periods t and t+1 is greater than 1, the energy consumption performance improves (productivity gains). On the other hand, when the total factor productivity index between two time periods t and t-+1 is smaller than 1, then the energy consumption performance declines (productivity loss).

Combining the above two steps, the final results of Table 1 are obtained. This table shows for each country and each year: i) the productivity gains (TFPCH>1) as a result of improvements in efficiency (TECHCH-EFFCH<0) and technological progress (TECHCH-EFFCH>0) and ii) productivity loss (TFPCH<1).

Table 1: Productivity gains as a result of improvements in efficiency and technological progress and productivity loss. Country names are defined in Figure 2

t	EU15	IE	LU	NL	FR	IT	ES	SE	AT	DK	FI	DE	BE	EL	PT	UK
1995-1996								Base year								
1996-1997	EFF [(a)]	EFF	EFF	EFF	EFF	TECH^{L} [(b)]	TECH^{L}	TECH^{L}	EFF	EFF	TECH [(c)]	TECH	EFF	TECH^{L}	EFF^{L} [(d)]	EFF
1997-1998	EFF	TECH^{L}	EFF	EFF	EFF	TECH^{L}	EFF^{L}	TECH^{L}	EFF	EFF	EFF^{L}=TECH^{L} [(e)]	EFF	EFF	TECH^{L}	EFF^{L}	EFF
1998-1999	EFF	EFF	EFF	EFF	EFF	TECH^{L}	EFF^{L}	EFF	EFF	EFF	EFF	EFF	EFF	EFF	EFF^{L}	EFF
1999-2000	TECH	TECH	TECH	TECH	EFF=TECH [(f)]	TECH	TECH^{L}	TECH	TECH	EFF	TECH	TECH	TECH	TECH^{L}	EFF^{L}	EFF
2000-2001	TECH	TECH^{L}	TECH^{L}	TECH^{L}	EFF	TECH	TECH^{L}	TECH^{L}	TECH^{L}	EFF	TECH^{L}	TECH^{L}	EFF	TECH	TECH	TECH
2001-2002	TECH	TECH	TECH^{L}	TECH	EFF	TECH^{L}	TECH	EFF	TECH	EFF	TECH^{L}	TECH	TECH	TECH	EFF^{L}	TECH
2002-2003	TECH^{L}	TECH	TECH^{L}	TECH^{L}	EFF	TECH^{L}	TECH^{L}	TECH	TECH	TECH	TECH^{L}	TECH^{L}	TECH	TECH^{L}	TECH	TECH
2003-2004	TECH	TECH^{L}	TECH^{L}	TECH	EFF	TECH^{L}	TECH^{L}	TECH^{L}	TECH	EFF	TECH^{L}	TECH^{L}	EFF	EFF	EFF^{L}	EFF
2004-2005	TECH	TECH	TECH	TECH	EFF	TECH	TECH	TECH^{L}	TECH^{L}	EFF	EFF	TECH	TECH	TECH	EFF^{L}	EFF
2005-2006	EFF	TECH^{L}	EFF	EFF	TECH	TECH	TECH	EFF	EFF	EFF	TECH^{L}	TECH	EFF	TECH	TECH	EFF
2006-2007	TECH	TECH	TECH	TECH^{L}	TECH	TECH	TECH^{L}	TECH^{L}	TECH	EFF	TECH	TECH	TECH	TECH	TECH	TECH
2007-2008	EFF	TECH^{L}	EFF	EFF	TECH	TECH	TECH	TECH^{L}	EFF	EFF	EFF	TECH^{L}	TECH^{L}	TECH	TECH	EFF
2008-2009	TECH	TECH	TECH	TECH^{L}	EFF	TECH	TECH	TECH	TECH	TECH	TECH^{L}	TECH	TECH	TECH	EFF^{L}	TECH
2009-2010	EFF^{L}=TECH^{L}	TECH^{L}	TECH^{L}	TECH^{L}	EFF	TECH^{L}	TECH^{L}	TECH^{L}	TECH^{L}	EFF	TECH^{L}	EFF^{L}	EFF	EFF	EFF=TECH	EFF
2010-2011	TECH	TECH	TECH	TECH	TECH	TECH	TECH	TECH	TECH	TECH	TECH	TECH	TECH	TECH^{L}	TECH	TECH

[a]**EFF:** Productivity gains as a result of improvements in Efficiency, [b]**TECH^{L}:** Technological Progress but productivity losses, [c]**TECH:** Productivity gains as a result of Technological Progress, [d]**EFF^{L}:** Improvements in Efficiency but productivity losses, [e]**EFF^{L}=TECH^{L}:** Efficiency change is equal to technological change in the case of productivity losses, [f]**EFF=TECH:** Efficiency change is equal to technological change in the case of productivity gains

5. Discussion

The next step of our analysis aims to provide an extra insight into assessing relative productivity. Taking into account the empirical results obtained in the previous section, we have a deeper understanding of the content of productivity changes among cross-country comparisons. This provides policy makers with more valuable reference material related to drawing up policies that aim to increase national productivity.

Therefore, based on Figure 2, the eco-inefficiency score indicates the evaluated DMU's distance from the best practice DMUs with different production mixes to the efficient frontier. The best practice DMUs (Ireland 2000, Italy 2000, Austria 2000, France 2000, Ireland 2009 and Sweden 2009) appear equally attractive for inefficient DMU, which has the flexibility to choose an improvement direction that maximizes its efficiency. The DMUs with a high eco-efficiency are those situated in the upper right corner of the two frontiers of Figure 2, where they produce higher desirable outputs with the lowest undesirable outputs. These countries are France 2000 and Sweden 2009. The DMUs located on the frontier are considered eco-efficient, because no other DMUs can produce more desirable outputs and fewer undesirable outputs.

If a DMU fails to achieve an output combination on its production possibility frontier and falls beneath this frontier, then it is said to be technically inefficient, as it gets further away from the more efficient countries (e.g. Belgium 2000/2009, Greece 2000/2009, Netherlands 2000/2009).

In Figure 2, technological progress shifts upwards the production possibility frontier, as more outputs are obtainable using the same level of inputs. It can be seen from Figure 3 that the frontier shifts to the left, indicating the occurrence of technological progress from 2000 to 2009, as in the case of Sweden. In the absence of technological progress or improvement, an economy (e.g. Greece, Belgium, Netherlands) is found more and more far from the best practice countries, or driven to the simultaneous increase (Luxembourg, Finland) or decrease (Italy) of both GDP production and CO_2 emissions (Figure 3).

The simultaneous increase of GDP production (desirable output) and decrease of CO_2 emissions (undesirable output) can only be achieved through technical progress that affect the ability to optimally combine inputs and outputs.

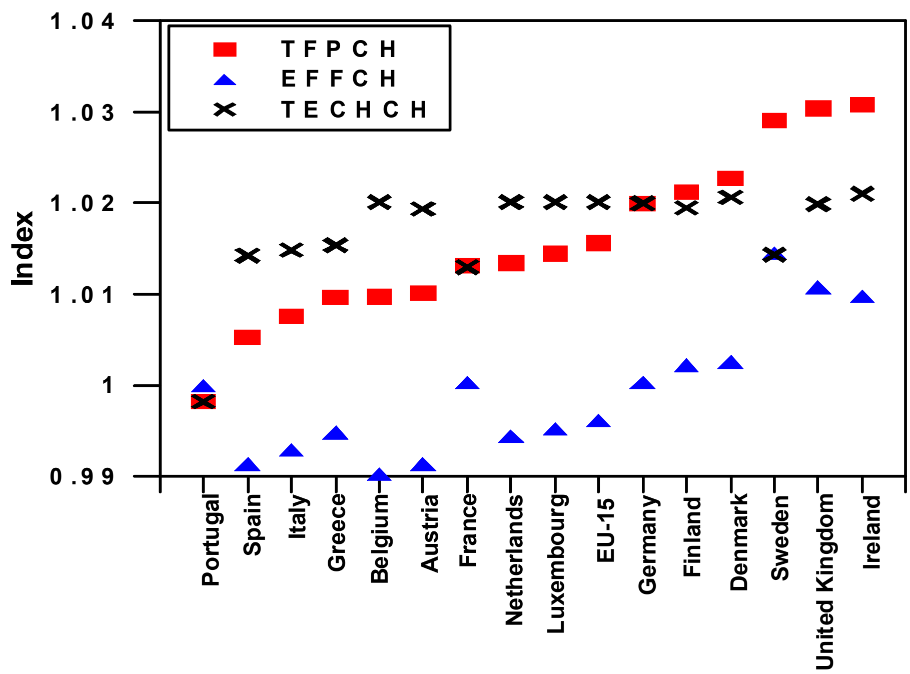
Combining the results depicted in Figure 2 and Figure 3, one can see whether the use of input (total energy consumption) or CO_2 emissions is the driving force of productivity growth. Therefore, an overall conclusion can be drawn regarding whether the overall development is driven by input-saving or by environmental-saving factors.

As shown in Figure 4 and Table 1, the detailed decomposition of total factor productivity change offers additional insights for policy implications, representing the driving forces of productivity gains or losses for the entire EU15 and for each of the individual EU15 countries. Therefore, it illustrates the nature of the overall productivity change that shapes up the Malmquist index.

More specifically, from this analysis one can see when the possible effect is characterized as EFF (productivity gains as a result of improvement in efficiency), TECH (productivity gains as a result of technological progress), EFF^L (improvement in efficiency but productivity losses), $TECH^L$ (technological progress but productivity losses), EFF=TECH (efficiency change is equal to technological change in the case of productivity gains), and $EFF^L = TECH^L$ (efficiency change is equal to technological change in the case of productivity losses) (see Table 1).

Figure 5 reports the average values of the Malmquist (TFPCH) index and its components (EFFCH, TECHCH) for the EU15 countries. The greatest increases of the TFPCH index are observed in Ireland, UK and Sweden, whereas the lowest ones in Portugal, Spain and Italy.

Figure 5: Annual means of Malmquist index and its components. Countries are sorted in ascending order by the TFPCH index.



The analysis of eco-efficiency changes (EFFCH) shows that, the average eco-efficiency change is positive (higher than one) for 7 of 16 DMUs. These are Sweden, UK, Ireland, Denmark, Finland, Germany and France, indicating that these DMUs have caught up the eco-efficiency benchmarks.

From the above countries, Sweden, UK, Ireland and Denmark, have the highest values of EFFCH in 1995-2011 due to their orientation of exploiting cleaner forms of energy, through gradual substitution procedures between fossil and non fossil fuels. The more a DMU abstains from the consumption of fossil fuels, the greater the divergence between the desirable (GDP) and the undesirable output (CO_2) (see also Figure 1). This happens because the maximization of the desirable output (GDP) comes with the temporal stabilization or decrease of the undesirable byproduct. This procedure is related to how effective is the energy mix and, therefore, how effectively the inputs are transformed into outputs using the available technology.

However, it is the average technical change that contributes most to productivity gains (TFPCH) (Figure 5), as it describes the change of the frontier (Figure 3) and, therefore, the best performers of the sample and not the development of the DMUs under the frontier (Figure 2). Our results are similar to those reported in the study conducted by Makridou *et al.* (2016), who concluded that technology change is primarily responsible for the improvements achieved in most sectors.

The results of the model show that the average TECHCH index is positive (higher than one) and greater than the average EFFCH index in all countries, except Portugal where there is an average decrease of 0.18% in the sample period.

The results on Figure 5 suggest that if the annual average growth of EFFCH is higher than one and lower than the annual average growth of TECHCH, then productivity gain (TFPCH), which is primarily the result of technological progress, have the highest value. Thus, the best DMUs of the sample, with the highest values of TFPCH index, are identified in the case of Ireland, United Kingdom, Sweden, Denmark, Finland and Germany. In the case of Sweden, the annual average growth of EFFCH (1.45%) is almost equal to the annual average growth of TECHCH (1.44%).

On the other hand, if the annual average growth of EFFCH is lower than one and lower than the annual average growth of TECHCH, which is higher than one, then productivity gain (TFPCH), which is primarily the result of technological progress, have the lowest value. Thus, the worst DMUs of the sample with the lowest values of TFPCH index are identified in the case of EU15, Luxembourg, Netherlands, France, Austria, Belgium, Greece, Italy and Spain. In the case of France, the annual average growth of EFFCH is positive (higher than one) with an average increase of 0.03% (Figure 5).

6. Conclusions and policy implications

This study develops an input oriented DEA model, aggregating both energy productivity and environmental degradation into a comprehensive index of Total Factor Productivity (Malmquist), in order to evaluate a DMU's total factor productivity.

The results suggest that technical progress affecting the ability to optimally combine inputs and outputs is the main factor for the simultaneous increase of desirable output and decrease of undesirable byproduct for most DMUs for the sample period under examination. In the absence of technical progress, a DMU is either far from the best practice DMUs (e.g. Greece, Belgium, Netherlands), or driven to the simultaneous increase (Luxembourg, Finland) or decrease (Italy) of both GDP production and CO_2 emissions.

An assessment of each DMU's productivity for the sample period is summarized in the following cases:

i) Productivity gains are due to an improvement in efficiency,

ii) Productivity gains are due to technological progress,

iii) There is an improvement in efficiency, but the productivity decreases,

iv) There is technological progress, but the productivity decreases,

v) There are productivity gains when efficiency change is equal to technological change,

vi) There is productivity loss when efficiency change is equal to technological change.

As shown from the analysis, the highest values of productivity gains (TFPCH) can be achieved in the case where the annual average growth of EFFCH is higher than one and lower than the annual average growth of TECHCH (Ireland, United Kingdom, Sweden, Denmark, Finland, Germany). On the other hand, the lowest values of productivity gains (TFPCH) appears when the annual average growth of EFFCH is lower than one and lower than the annual average growth of TECHCH (EU15, Luxembourg, Netherlands, France, Austria, Belgium, Greece, Italy and Spain).

The methodology utilized here and the results obtained capture the different causes of losses or gains in DMU's productivity from year to year. This work quantifies the inefficiency of the DMUs under the frontier, through the indicators of EFFCH, TECHCH and TFPCH. Such an approach is of particular importance in encouraging inefficient DMUs to always compare themselves with efficient DMUs in their range, and thus to make progress and improvements.

The obtained results have important implications for the policy makers to promote productivity performance of the energy sector in EU-15 countries. The detailed decomposition of productivity change into efficiency change, technology change, innovation efficiency and technology catch-up effect offers a better understanding of the content of the productivity change through the cross-country comparisons. That decomposition points out the driving forces of productivity gains or losses for the entire

EU15 and for each of the individual EU15 countries and thus offers additional insights for policy implications. For instance, policy actions intended to improve productivity gains (decrease productivity losses) might be misdirected if they focus (if they choose not to focus) on accelerating the rate of innovation, in the case where the productivity gains (productivity losses) are mainly the result of improvements in efficiency. Therefore, the present study provides more reference material to policy makers so as to draw up policies in order to elevate national productivity for the purpose of designing energy development strategy in EU-15 countries.

In order to quantify the huge efficiency gap so as to address the wasteful use of exhaustible energy inputs and reduce the environmental degradation, we calculate the distance for an inefficient DMU to the production frontier, through the DEA based Malmquist productivity index. In many cases, the distance of a specific DMU from the best practice DMUs indicates different production combination of desirable and undesirable outputs, and, therefore different alternatives for an inefficient DMU to choose a direction that maximizes its efficiency. The direction that an inefficient DMU should take and the amount of reduction of the energy consumption can be the basis for a government to establish energy saving policies and to strengthen energy management, especially in the cases where large amounts of energy input are necessary in the economy, but with low value added. An energy management system is one of the most important factors in the context of strengthening energy efficiency policy as it allows in energy efficiency issues to gain a greater priority within the DMU.

This analysis allows policy makers of EU states to identify the explanatory causes behind final energy consumption and therefore the determinants of productivity change.

In this sense, it is very important to identify the economic activities that, due to their impact, are essential to reduce energy consumption, as well as potential strategies and measures to improve the efficiency of final energy use. For example, restructuring of industry, developing programs of technology innovation and encouraging the reuse of input resources can be some of the directions to follow in the context of strengthening energy efficiency policies.

It is necessary for policy makers to promote technological innovation on energy saving and emission reduction. To realize this purpose, it is absolutely essential to increase research investment to develop environmental technology, energy saving technology and low-carbon technology in order to limit excessive energy consumption and pollutant emissions.

In this way, technological innovation has an additive significant contribution on strategies of optimizing industrial structure as it manages to accelerate the development of environmental-friendly industries.

Thus, the results obtained here can be used as a guide for policy makers to promote the best efficiency measures for a given level of resources use over the same period. Furthermore they can serve as a useful tool for policy making by investigating the gradual process of the diffusion and adoption of new technologies. Also, they can be used to optimize the management of energy resources in order to achieve the highest productivity gains of DMUs over time.

References

Apergis, Nicholas, Goodness C. Aye, Carlos Pestana Barros, Rangan Gupta, and Peter Wanke. (2015). Energy efficiency of selected OECD countries: A slacks based model with undesirable outputs, *Energy Economics* 51: 45-53.

Bampatsou, Christina, and George Hadjiconstantinou. (2009). The use of the DEA method for simultaneous analysis of the interrelationships among economic growth, environmental pollution and energy consumption, *International Journal o f Economic Sciences and Applied Research* 2 (2): 65-86.

Bampatsou, Christina, Savas Papadopoulos, and Efthimios Zervas. (2013). Technical efficiency of economic systems of EU-15 countries based on energy consumption. *Energy Policy* 55: 426-434.

Bevilacqua, Maurizio, and Marcello Braglia. (2002). Environmental efficiency analysis for ENI oil refineries, *Journal of Cleaner Production* 10 (1): 85–92.

Caves, Douglas W., Laurits R. Christensen, and W. Erwin Diewert. (1982). The Economic Theory of Index Numbers and the Measurement of Input, Output, and Productivity. *Econometrica* 50(6): 1393–1414.

Chames, Abraham, William W. Cooper, and Edwardo L. Rhodes. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research* 2 (6):429-444.

Charnes, Abraham, William W. Cooper, Arie Y. Lewin, and Lawrence M. Seiford. (1993). *Data Envelopment Analysis: Theory, methodology, and application*, Boston: Kluwer Academic Publishers.

Chen, Chien-Ming, and Magali A. Delmas. (2012).“Measuring Eco-inefficiency: A New Frontier Approach, *Operations Research* 60: 1064–1079.

Corrado, Carol, Hulten Charles, and Daniel Sichel. (2005). “Measuring Capital and Technology: An Expanded Framework,” in *Measuring Capital in the New Economy*, C. Corrado, J. Haltiwanger, and D. Sichel, (Eds.), Studies in Income and Wealth, 65: 11-41, Chicago: The University of Chicago Press for the National Bureau of Economic Research. http://econweb.umd.edu/~hulten/webpagefiles/Measuring%20Capital%20and%20Technology%20%20An%20Expanded%20Framework.pdf

Corrado, Carol, Charles Hulten, and Daniel Sichel. (2009). “Intangible Capital and U.S. Economic Growth,” *Review of Income and Wealth* 55 (3): 661-685.

EIA. (2013). International Energy Annual. Energy Information Administration, U.S. Department of Energy. http://www.eia.doe.gov/iea/contents.html [accessed date: 06 October, 2013].

Fagerberg, Jan. (1994). Technology and International Differences in Growth Rates, *Journal of Economic Literature* 32(3): 1147–1175.

Färe, Rolf, and C. A. Knox Lovell. (1978). Measuring the technical efficiency of production, *Journal of Economic Theory* 19 (1): 150-162.
.
Färe, Rolf., Shawna Grosskopf, and C. A. Knox Lovell. (1994a). *Production Frontiers*, Cambridge: Cambridge University Press.

Färe, Rolf, Shawna Grosskopf, Mary Norris, and Zhongyang Zhang. (1994b). Productivity Growth, Technical Progress, and Efficiency Change in Industrialized Countries, *The American Economic Review* 84(1): 66–83.

Färe, Rolf, Shawna Grosskopf, and Pontus Roos. (1995). Productivity and quality changes in Swedish pharmacies, *International Journal of Production Economics* 39 (1–2): 137-144.

Farrell, Michael J. (1957). The Measurement of Productive Efficiency, *Journal of the Royal Statistical Society*. *Series A (general)* 120(3): 253-290.

Fischer, Manfred M., Thomas Scherngell, and Martin Reismann. (2009). Knowledge spillovers and total factor productivity: evidence using a spatial panel data model, *Geographical Analysis* 41(2): 204–220.

Fixler, Dennis, and Kimberly D. Zieschang. (1992). "Incorporating Ancillary Measures of Process and Quality Change into a Superlative Productivity Index," *Journal of Productivity Analysis* 2(4): 245-267.

Fried, Harold O., C. A. Knox Lovell, and Shelton S. Schmidt, (2008). *The Measurement of Productive Efficiency and Productivity Change*, New York: Oxford University Press.

Fukuyama, Hirofumi, Hiroya Masaki, Kazuyuki Sekitani, and Jianming Shi. (2013). Distance optimization approach to ratio-form efficiency measures in data envelopment analysis, *Journal of Productivity Analysis* 42(2): 175-186.

Golany, Boaz, and Sten Thore. (1997). The economic and social performance of nations: efficiency and returns to scale, *Socio-Economic Planning Sciences* 31(3): 191-204.

Halkos G. (2010). Construction of abatement cost curves: The case of F-gases, MPRA Paper **26532**, University Library of Munich, Germany.

Halkos G. (2014). The Economics of Climate Change Policy: Critical review and future policy directions, MPRA Paper **56841**, University Library of Munich, Germany.

Halkos G and Salamouris (2004). Efficiency measurement of the Greek commercial banks with the use of financial ratios: a data envelopment analysis approach. *Management Accounting Research* 15 (2): 201-224.

Halkos G. and Tsilika K. (2014). Analyzing and visualizing the synergistic impact mechanisms of climate change related costs, MPRA Paper **55459**, University Library of Munich, Germany.

Halkos G. and Tsilika K. (2016). Climate change impacts: Understanding the synergetic interactions using graph computing, MPRA Paper **75037**, University Library of Munich, Germany.

Halkos G. and Paizanos E. (2016). The effects of fiscal policy on CO2 emissions: Evidence from the U.S.A, Energy Policy, 88(C), 317-328.

Halkos G. and Polemis M. (2016). The good, the bad and the ugly? Balancing environmental and economic impacts towards efficiency, MPRA Paper **72132**, University Library of Munich, Germany.

Halkos G. and Skouloudis A. (2015). Exploring corporate disclosure on climate change: Evidence from the Greek business sector, MPRA Paper **64566**, University Library of Munich, Germany.

Kitcher, Ben, Ian P. McCarthy, Sam Turner, and Keith Ridgway. (2013). Understanding the effects of outsourcing: unpacking the total factor productivity variable, *Production Planning & Control: The management of Operations* 24 (4-5): 308–317.

Kortelainen, Mika. (2008). Dynamic environmental performance analysis: A Malmquist index approach, *Ecological Economics* 64(4): 701–715.

.

Kuo, Renjieh J., Y. C. Wang, and Fanchih C. Tien. (2010). Integration of artificial neural network and MADA methods for green supplier selection, *Journal of Cleaner Production* 18(12): 1161–1170.

Long, Xingle, Xicang Zhao, and Faxin Cheng. (2015). The comparison analysis of total factor productivity and eco-efficiency in China's cement manufactures, *Energy Policy* 81: 61-66.

Mahlberg, Bernhard, Mikulas Luptacik, and Biresh K. Sahoo. (2011). Examining the drivers of total factor productivity change with an illustrative example of 14 EU countries, *Ecological Economics* 72: 60-69.

Makridou, Georgia, Kostas Andriosopoulos, Michael Doumpos, and Constantin Zopounidis. (2015). A Two-stage approach for energy efficiency analysis in European Union countries, *The Energy Journal* 36 (2): 47-69.

Makridou, Georgia, Kostas Andriosopoulos, Michael Doumpos, and Constantin Zopounidis. (2016). Measuring the efficiency of energy-intensive industries across European countries, *Energy Policy* 88: 573-583.

Malmquist, Sten. (1953). Index numbers and indifference surfaces, *Trabajos de Estadistica* 4(2) : 209-242.

Murillo-Zamorano, Luis R. (2005). The Role of Energy in Productivity Growth: A Controversial Issue?, *The Energy Journal* 26 (2): 69-88. 10.5547/ISSN0195-6574-EJ-Vol26-No2-4

OECD. (2013). Gross Domestic Product (GDP) in national currency, in current prices and constant prices (national base year, previous year prices and OECD base year i.e. 2005), Organisation for Economic Co-operation and Development. http://stats.oecd.org/ [accessed date: 04 October, 2013].

Pardo Martínez, Clara I. (2013). An analysis of eco-efficiency in energy use and CO_2 emissions in the Swedish service industries, *Socio-Economic Planning Sciences* 47(2):120-130.

Ramanathan, Ramakrishnan. (2006). A multi-factor efficiency perspective to the relationships among world GDP, energy consumption and carbon dioxide emissions, *Technological Forecasting and Social Change* 73(5): 483-494. http://dx.doi.org/10.1016/j.techfore.2005.06.012.

Ramli, Noor Asiah., and Susila Munisamy. (2013). A Study on Eco-Efficiency of the Manufacturing Sector in Malaysia, *Actual Problems of Economics* 12(150): 480- 491. http://repository.um.edu.my/30015/1/A%20Study%20on%20Eco-Efficiency%20of%20the%20Manufacturing%20Sector%20in%20Malaysia%20-%20postprint.pdf.

Sarkis, Joseph, and Jeffrey Weinrach. (2001). Using data envelopment analysis to evaluate environmentally conscious waste treatment technology, *Journal of Cleaner Production* 9(5): 417-427.

Sheng, Yu, Yanrui Wu, Xunpeng Shi, and Dandan Zhang. (2015). Energy trade efficiency and its determinants: A Malmquist index approach, *Energy Economics* 50: 306-314.

Shephard, Ronald W. (1970). *Theory of Cost and Production Functions*. Princeton, New Jersey: Princeton University Press.

Shephard, Ronald W., and Rolf Färe. (1974). "The law of diminishing returns," *Zeitschrift für Nationalökonomie* 34 (1): 69–90.

Sueyoshi, Toshiyuki, and Yan Yuan. (2016). Marginal Rate of Transformation and Rate of Substitution Measured by DEA Environmental Assessment: Comparison among European and North American Nations, *Energy Economics*. 56(C): 270-287.

Wang, Ke, and Yi-Ming Wei. (2016). Sources of energy productivity change in China during 1997–2012: A decomposition analysis based on the Luenberger productivity indicator, *Energy Economics* 54:50-59.

Xishuang, Han, Xue Xiaolong, Ge Jiaoju, Wu Hengqin, and Su Chang. (2014). Measuring the Productivity of Energy Consumption of Major Industries in China: A DEA-Based Method, *Mathematical Problems in Engineering* 2014. http://dx.doi.org/10.1155/2014/121804.

APPENDIX A

Table A1: The difference between the two indexes of TECHCH and EFFCH

T	EU15	IE	LU	NL	FR	IT	ES	SE	AT	DK	FI	DE	BE	EL	PT	UK
1995-1996	Base year															
1996-1997	**-0.020**	**-0.003**	**-0.048**	**-0.043**	**-0.057**	0.022	0.045	0.042	**-0.006**	**-0.136**	0.012	0.004	**-0.041**	0.032	**-0.056**	**-0.085**
1997-1998	**-0.041**	0.015	**-0.102**	**-0.065**	**-0.062**	0.008	**-0.008**	0.013	**-0.045**	**-0.141**	0.000	**-0.026**	**-0.058**	0.018	**-0.068**	**-0.079**
1998-1999	**-0.051**	**-0.023**	**-0.036**	**-0.067**	**-0.064**	0.003	**-0.003**	**-0.036**	**-0.053**	**-0.147**	**-0.032**	**-0.034**	**-0.107**	**-0.045**	**-0.085**	**-0.059**
1999-2000	0.032	0.055	0.036	0.049	0.000	0.044	0.073	0.002	0.018	**-0.068**	0.041	0.064	0.016	0.062	**-0.025**	**-0.011**
2000-2001	0.035	0.061	0.055	0.043	**-0.004**	0.033	0.047	0.110	0.056	**-0.032**	0.048	0.053	**-0.028**	0.012	0.016	0.005
2001-2002	0.082	0.078	0.114	0.101	**-0.026**	0.043	0.017	**-0.021**	0.050	**-0.031**	0.093	0.074	0.046	0.003	**-0.036**	0.031
2002-2003	0.108	0.087	0.136	0.113	**-0.009**	0.094	0.066	0.003	0.078	0.076	0.167	0.118	0.093	0.054	0.005	0.027
2003-2004	0.019	0.042	0.077	0.020	**-0.006**	0.048	0.033	0.079	0.014	**-0.139**	0.022	0.021	**-0.042**	**-0.025**	**-0.005**	**-0.032**
2004-2005	0.040	0.067	0.063	0.065	**-0.039**	0.020	0.019	0.033	0.051	**-0.083**	**-0.036**	0.024	0.002	0.025	**-0.034**	**-0.023**
2005-2006	**-0.040**	0.032	**-0.059**	**-0.065**	0.008	0.026	0.008	**-0.003**	**-0.043**	**-0.019**	0.057	0.006	**-0.082**	0.022	0.074	**-0.052**
2006-2007	0.071	0.088	0.025	0.108	0.003	0.068	0.090	0.107	0.056	**-0.010**	0.100	0.043	0.040	0.075	0.005	0.019
2007-2008	**-0.026**	0.033	**-0.010**	**-0.085**	0.045	0.057	0.006	0.080	**-0.006**	**-0.110**	**-0.010**	0.029	0.011	0.019	0.105	**-0.026**
2008-2009	0.110	0.106	0.118	0.138	**-0.017**	0.045	0.032	0.052	0.122	0.061	0.179	0.140	0.024	0.092	**-0.042**	0.100
2009-2010	0.000	0.027	0.026	0.002	**-0.034**	0.024	0.001	0.091	0.013	**-0.062**	0.061	**-0.013**	**-0.045**	**-0.027**	0.000	**-0.027**
2010-2011	0.108	0.120	0.134	0.100	0.056	0.108	0.122	0.105	0.089	0.035	0.101	0.077	0.088	0.161	0.044	0.082

(The countries name is as in Figure 2)

Table A2: The index of total factor productivity change

T	EU15	IE	LU	NL	FR	IT	ES	SE	AT	DK	FI	DE	BE	EL	PT	UK
1995-1996	Base year															
1996-1997	1.0385	1.0207	1.0661	1.0619	1.0760	**0.9958**	**0.9723**	**0.9759**	1.0246	1.1558	1.0059	1.0136	1.0597	**0.9860**	**0.9443**	1.1036
1997-1998	1.0277	**0.9715**	1.0885	1.0514	1.0483	**0.9785**	**0.9952**	**0.9736**	1.0319	1.1267	**0.9866**	1.0127	1.0441	**0.9693**	**0.9323**	1.0653
1998-1999	1.0433	1.0158	1.0291	1.0591	1.0566	**0.9899**	**0.9960**	1.0287	1.0457	1.1393	1.0247	1.0271	1.0997	1.0379	**0.9153**	1.0516
1999-2000	1.0365	1.0120	1.0321	1.0184	1.0475	1.0177	**0.9750**	1.0558	1.0488	1.1397	1.0255	1.0025	1.0529	**0.9852**	**0.9747**	1.0789
2000-2001	1.0017	**0.9751**	**0.9810**	**0.9931**	1.0389	1.0057	**0.9887**	**0.9253**	**0.9820**	1.0702	**0.9893**	**0.9838**	1.0651	1.0245	1.0163	1.0331
2001-2002	1.0272	1.0312	**0.9935**	1.0073	1.0533	**0.9904**	1.0139	1.0496	1.0177	1.1250	**0.9818**	1.0152	1.0656	1.0284	**0.9638**	1.0452
2002-2003	**0.9964**	1.0199	**0.9672**	**0.9920**	1.0301	**0.9524**	**0.9746**	1.0278	1.0009	1.0211	**0.9222**	**0.9711**	1.0124	**0.9907**	1.0052	1.0574
2003-2004	1.0057	**0.9768**	**0.9466**	1.0043	1.0308	**0.9735**	**0.9885**	**0.9423**	1.0034	1.1554	**0.9937**	**0.9959**	1.0669	1.0459	**0.9953**	1.0496
2004-2005	1.0307	1.0001	1.0076	1.0050	1.0547	1.0087	1.0117	**0.9905**	**0.9994**	1.1396	1.0908	1.0290	1.0705	1.0071	**0.9663**	1.0766
2005-2006	1.0409	**0.9667**	1.0608	1.0669	1.0547	1.0195	1.0340	1.0569	1.0592	1.0282	**0.9552**	1.0067	1.0836	1.0154	1.0737	1.0654
2006-2007	1.0363	1.0205	1.0853	**0.9975**	1.0625	1.0047	**0.9859**	**0.9608**	1.0400	1.1181	1.0017	1.0574	1.0693	1.0086	1.0053	1.0813
2007-2008	1.0213	**0.9679**	1.0057	1.0808	1.0347	1.0115	1.0557	**0.9913**	1.0332	1.1286	1.0239	**0.9906**	**0.9841**	1.0264	1.1045	1.0518
2008-2009	1.0173	1.0380	1.0082	**0.9874**	1.0829	1.0274	1.0533	1.0161	1.0265	1.0897	**0.9638**	1.0094	1.1084	1.0272	**0.9584**	1.0475
2009-2010	**0.9810**	**0.9618**	**0.9557**	**0.9793**	1.0226	**0.9649**	**0.9887**	**0.8996**	**0.9825**	1.0572	**0.9280**	**0.9988**	1.0260	1.0190	1.0005	1.0218
2010-2011	1.0571	1.0521	1.0295	1.0659	1.0888	1.0366	1.0226	1.0548	1.0798	1.1501	1.0647	1.0905	1.0784	**0.9873**	1.0445	1.0981

(The countries name is as in Figure 2)