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The use of the DEA method for simultaneous analysis of the interrelationships among economic growth, environmental pollution and energy consumption

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Abstract

In this study Data Envelopment Analysis (DEA) is used not only to develop an efficiency index which combines economic activity, CO2 emissions and energy consumption of the production process in the 31 countries of Europe for the year 2004, but also to make estimates about the margins of long term increase or decrease in the consumption levels of exhaustible energy resources of a selected sample (Switzerland, Greece, United Kingdom, and Luxembourg) of European countries (out of 31) which belong to the high income group of OECD members.As shown, each country can achieve better TE when its increased economic activity is combined with improved ecological performance. It can be noticed from the analysis that the developed economies that tend to stabilize their environmental degradation through time (Switzerland), as the GDP (per capita GDP) increases, ensure satisfactory margins for the increase in the consumption of the 'dirty' energy index (DEI) in the long term, and thus contribute to sustainable economic development. This fact is significantly different in countries showing either intense deterioration (Greece) or temporary improvement (United Kingdom, Luxemburg) in the pollution levels without any indications of a temperate stabilization of environmental degradation.

Keywords: Technical Efficiency index, Sustainability, Energy Consumption, Environmental Pollution, Economic Development, DEA, Future Estimations.

JEL classification: Q01, Q32.

1. Introduction

The Data Envelopment Analysis (DEA) developed by (Charnes *et al* in 1978, is one of the most established methods for assessing efficiency and comparative analysis of Decision Making Units (DMUs) which function in a system that consists of uniform units.

The (DEA) method is based on a model of linear programming in order to define the TE levels, in cases of constant or variable returns to scale. The DEA in particular can be carried out either with the assumption of Constant Returns to Scale

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(CRS)[1] (Thanassoulis, 2001) according to the model of (Charnes *et al.*, 1978) or with the assumption of Variable Returns to Scale (VRS)[2] (Thanassoulis, 2001) according to the model of (Banker *et al.,*1984).

Furthermore, the technical efficiency as defined by the DEA method for constant or variable returns to scale, can be calculated either based on output orientation, thus resulting in a model that attempts to maximize outputs holding the observed amount of any input constant, or based on input orientation thus resulting in a model whose objective is to minimize inputs, keeping the observed amount of any output constant (Coelli et al., 2005).

In the present study, the Technical Efficiency index (TE) is defined as an output maximization linear programming problem for constant inputs, applied for constant returns to scale. This index (TE) which functions as an efficiency measure of the productive process in the economic systems of the Decision Making Units (DMUs) (which are European countries), is related to how well the inputs are transformed into outputs.

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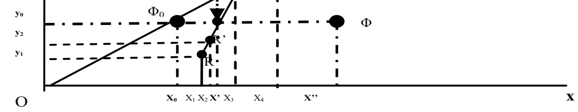
[1] In the DEA model of Constant Returns to Scale (CRS) (Charnes, Cooper and Rhodes (1978)), the more x increases (which constitute the inputs or, in other words, the production factors used in the productive process), the more y increases (which constitute the output produced), at an equivalent quota. E.g. if the number of the productive factors is doubled, then the quantity of the output is doubled as well). Diagram 1 shows how an input (x) is used to produce an output (y). If assumed that the output is changed in direct proportion to the input (Constant Returns to Scale), the efficiency frontier is defined by a straight line starting from the beginning of the axes (which determine the production function) and passes through the point of the unit with the highest ratio of outputs to inputs (Charnes *et al.*, 1978). These units are (Φ_0 or P). Unit (Φ)-is 'inefficient' since it could produce the same amount of output with less amount of input by ($X''-X_0$). The inefficiency of Φ is determined by the ratio $TE=y_0\Phi_0/\ y_0\Phi$.

[2] In the case of Variable Returns to Scale (VRS), when x increases then y increases either less (descending returns to scale), or more (increasing returns to scale) than the increasing quota of x.

The DEA model of Variable Returns to Scale (Banker, Charnes and Cooper (1984)) is chosen when it is not previously known if a percentage change of inputs would cause an equivalent percentage change in output/s. More specifically, in the case of increasing organizational complexity of the DMUs due to an increase in the size and the variety of their activities, the outputs are not modified in a way directly proportional to the inputs (Variable Returns to Scale) (Banker *et al.*, 1984). According to (Diagram 1), the DMUs R, R', P, P' that are found on the curve of the variable returns to scale are efficient. The efficiency frontier is formed if the efficiency data (outputs/inputs) of the specific DMUs are joined with straight lines. As a result, concerning VRS, the inefficiency of the organization (Φ) is expressed using the ratio $TE=y_0\Phi'/\ y_0\Phi$. This ratio shows that the magnitude of inefficiency is less in this case than when we have constant returns to scale such as $OX'/OX'' > OX_0/OX''$.

Diagram 1: Determination of TE both in Constant and Variable Returns to Scale



- A move from R → to R' on VRS, states increasing returns to scale
- A move from P → to P' on VRS, states decreasing returns to scale

Source: Adapted from Charnes A., Cooper W.W., Rhodes E., (1978), 'Measuring the efficiency of decision making units', *European Journal of Operational Research,* 2: 429-444.

The cases where the index has high values are a result of the countries' orientating towards exploitation of cleaner forms of energy, through gradual substitution procedures between dirty and clean energy. The more a country abstains from the consumption and flaring of fossil fuels, the greater the convergence between the quantitative increase and the qualitative improvement of the product (total output) since the maximization of the desirable output (GDP) comes with the diachronic stabilization of the undesirable byproduct and therefore from the preservation of exhaustible natural resources stock or alternatively of fossil fuels (oil, coal, and natural gas). The qualitative improvement of the product can guarantee a) the stabilization of environmental degradation by controlled exploitation of fossil fuels and b) better prospects for a long-term sustainable economic activity.

2. Definition of sustainable economic development

The concept of sustainability which refers to development (qualitative improvement of the product) (Pezzey, 1989; Toman, Pezzey and Krautkraemer, 1995) rather than to growth (the quantitative increase of the product (i.e. increase of Gross Domestic Product)) – *according to Herman Daly's definition that sustainable development is 'development without growth in throughput of matter and energy beyond regenerative and absorptive capacities.'* Renders the concepts of sustainability and growth totally incompatible. The theoretical approaches to the subject of sustainable economic activity are those of environmental economics (as a subset of neoclassical economics) and of ecological economics. In particular, neoclassical economics claim that the sustainability of economic systems is achieved by economic growth processes whereas ecological economics support economic development.

In the neoclassical approach of environmental economics the relation between economy and environment is clearly explained. No longer does the welfare or the utility analysis depend only on consumption levels, but also on other factors, such as the environmental quality, natural resource stock, and pollution (Grossman *et al.*, 1995; Wagner, 2006). In this case, the productive process is the result of the combination of capital, labor and natural resources, while the pollution factor is an externality, something which leads to failure to fully assess the environmental degradation (Goodland et al., 1987). For instance, according to environmental economics, the scarcity of the natural resources which is reflected in the market system through the gradual increase in the price of these resources, is 'treated' by procedures of continuous substitution between the industrial and natural capital, of full recycling of the material, whenever possible, and by using various technological innovations in the production process. According to neoclassical economics, these mechanisms render the economic system effective and guarantee continuous economic growth without having to impose certain limits on the economic activity.

On the other hand, the connection between ecosystems and economic systems is the structure of the so-called 'arising new paradigm'. In this case, not only do we have the relationship between the economic system and the environmental system (in which all forms of life are preserved) but also the culture, technology, organization of politicoeconomic system, and the size of population, which constitute compound elements of the multilateral ecological system (Christensen, 1989). In ecological economics, the economic development is regarded as an improvement of the natural dimensions of the economy. The productive process is examined as a process of material transformation through the use of energy and the use of capital and labor, considering the waste as an inevitable by-product. Great importance is placed on the differentiation between individual and social values, as well as on the evolution, preservation of mass, non-irreversibility, and the possibility of a gradual substitution among certain natural resources (Hediger, 1997) as the substitution possibilities among the various capital forms (i.e. between manufactured and natural capital) are quite limited and even nonexistent at times (Daly, 1992, Turner and Pearce 1992). Supporters of ecological economics insist on the fact that the damages inflicted on nature and the environment can lead to a potential ecological devastation through continuous economic growth. Furthermore, they are very worried about the adaptability levels of the ecosystems which depend on the complex links between the global geo-biochemical procedures and on the biosphere functions related to 'life provision' and are signi-ficantly aggravated due to human activities.

In this paper, which forms a part of the theoretical setting of ecological economics, the concept of Economic Development refers to a combination of both quantitative and qualitative dimensions. The definition of the TE index, through the Data Envelopment Analysis (DEA) method, successfully describes the intense interaction between ecological performance and economic activity. This index is a clear indication both of the levels of sustainability of the economic activity – as at the same time it calculates the intense interrelation between environmental pollution, energy consumption, and economic activity in the productive process (Ramanathan, 2002) – and the long term possibilities of gradual substitution[3] among energy resources.

3. DEA characteristics

The DEA is an alternative non-parametric approach, in which the evaluation of the efficiency of the system is carried out with empirical data, without formerly adopting specific production functions that relate inputs with outputs. It is important that the DEA is not influenced by a small data sample. So that comparative evaluation between two or more DMUs is achieved, the methodology can be used for a combination of inputs/outputs that consists of at least two inputs and one output or two outputs and one input. This technique is not bound by the units of measurement of multiple inputs-outputs, since they can differ significantly.

These characteristics of the DEA method, and in particular a) the lack of commitment to using a specific production function that relates input(s) to output(s) and b) the possibility of using simultaneous multiple inputs and outputs, which can be specified by different units of measurement, provide the researcher with the possibility of undertaking alternative approaches, alternative input and output combinations and thus more in-depth examination of complicated issues.

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[3] The substitution possibilities for sustainability concern either the DEI and CEI indexes, or the partial DEI indicators (e.g. substitution of the more dirty oil and coal indexes with the less dirty natural gas, which, however, is still exhaustible like the other two).

This paper is centered on sustainable economic development procedures and not on economic growth procedures. This means that the result of the production process is not limited to the GDP production but integrates the environmental degradation factor (CO2 emissions) as an inevitable byproduct of the production process (Lozano and Gutierrez 2008). The input, which in this case is responsible for the simultaneous production of both the desirable product (GDP) and the undesirable byproduct (CO2 emissions, from the consumption and flaring of fossil fuels) is the total energy consumption, composed of the renewable and exhaustible energy resources.

In contrast to the econometric approaches that attempt to define the absolute efficiency of the organization in relation to one comparative reference point (benchmark) that has been externally defined as standard, the non-parametric or non-econometric approaches aim to evaluate the efficiency of an organization either with another DMU in the same system of uniform units (European countries), or with a combination of DMUs. As a consequence, DEA constitutes a good evaluation standard of the relative efficiency of a DMU, but not of the absolute efficiency, as there is no comparison with what is regarded as maximal (Cooper *et al*., 2006).

Furthermore, the DEA which actually embodies all the production possibilities that are observed for a specific sample of uniform Decision Making Units (DMUs), adopts a linear programming approach so as to produce a non-parametric linear curved frontier, so that all studied units are enveloped by this frontier (Thanassoulis, 2001). By using this empirical frontier[4], based on the DEA method, the efficiency levels of each

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[4] Definition of the Efficiency Frontier through an output oriented model of Constant Returns to Scale: In order to define the Efficiency Frontier through an output oriented model of Constant Returns to Scale, we take the simple case of two outputs and one input. By comparing the combination of the existing and the optimal inputs and outputs, the so called efficiency frontier is formed, which represents the best practice technology. The efficiency frontier is formed by a line joining the adjacent points corresponding to those organizations (countries) that in the production function present the highest ratio of outputs to inputs. As such, the frontier formed by such a procedure covers the non-efficient Decision Making Units as well (Cooper *et al*., 2006).

The 'Units' found on the efficiency frontier (which represents the best practice technology), are characterized as 'Units' of full efficiency or best practice 'Units' and they are no other than the units/countries with the most effective combinations of production factors for a specific period of time (Cooper *et al.,*2006). The maximum efficiency is defined in relation to the various production possibilities that result from the already existing mixture of inputs and outputs, so that the outputs can be maximized by using available inputs (output oriented efficiency) (Coelli *et al*., 2005) (Diagrams 2, 3). The most efficient 'Unit' becomes the benchmark for the other units/countries, the efficiency deficit of which is determined by their distance from the frontier.

Alternatively, the efficiency frontier serves the benchmarking of goals and constitutes a point for comparative analysis of the inefficient 'Units', since the deficit 'Units' can under certain circumstances imitate the productive practices that best practice 'Unit' implements, and thus become efficient themselves.

For example, the inefficiency of a 'Unit K' (Diagram 3) depends on its distance from the efficiency frontier for a specific mixture of inputs and outputs which is exclusive to 'Unit K'. Consequently, the distance of an inefficient unit/country from the efficiency frontier expresses the lack of its efficiency, which is related to how much it must improve in order to become efficient.

(DMU) are determined by their distance from the frontier (Diagrams 2, 3). In this way, all the potential efficient combinations of outputs that a ‘Unit’ can produce at a specific time can be described. It is all about a non-stochastic approach, since it considers that every deviation from the frontier is the result of the lack of efficiency. When considering large problems, the separate application of linear programming for every DMU results in intensified calculations, thus placing the method at a dis-advantage.

The non-parametric nature of the DEA method does not allow for the application of statistical tests since the statistical error that can be caused by lack of data, measurement errors, etc. is not taken into account. Even if the noise is regular with zero mean, it can cause important problems in the evolution of an empirical analysis. It is important that what the DEA considers as ‘inefficiency’, for the parametric econometrical methods it is a combination of two components: the real ‘inefficiency’ and the statistical error. On the other hand, being a non-parametric method (in which the efficiency is calculated without considering parameters), DEA provides the researchers a significant freedom in defining inputs, outputs and production functions.

4. The model (DEA formulation)

The DEA is a multi-factor productivity analysis model for measuring the relative technical efficiencies of a homogenous set of decision making units (DMUs). This index, in the presence of multiple input and output factors, is defined as: The ratio of the sum of outputs to the sum of inputs that have been weighed with weighted factors

$$TE = \frac{\text{Weighted Sum of Outputs}}{\text{Weighted Sum of Inputs}} \qquad (1)$$

It is characteristic that DEA gives separate weights to each input and output, weights which are extracted after all possible linear combinations of peer DMUs (which produce at least the same result as the Decision Making Unit examined) have been checked.

Diagram 2: Output orientation in the case of Constant Returns to scale

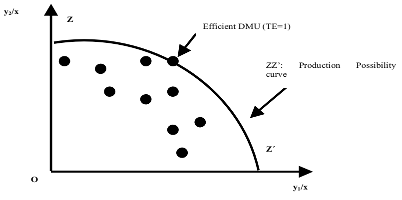
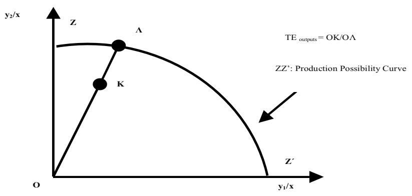


Diagram 3: TE in the case of output orientation based on Constant Returns to Scale



Source: Cooper W., Seiford Lauwrence M., Tone Kaoru, (2006), *Introduction to Data Envelopment Analysis and its uses with DEA-Solver Software and References*, Springer, USA.

Assuming that there are n DMUs, with m inputs and s outputs each, the level of relative efficiency of one of them (even of p DMU) arises as a result of the solution of the following model, described by (Charnes et al., 1978):

$$\max \frac{\sum_{k=1}^{s} v_k y_{kp}}{\sum_{j=1}^{m} u_j x_{jp}} , \qquad \text{s.t} \ \frac{\sum_{k=1}^{s} v_k y_{ki}}{\sum_{j=1}^{m} u_j x_{ji}} \le 1, \qquad \forall i \ \ v_k , u_j \ge 0 \ , \qquad \forall k, j \quad (2)$$

where

k=1 to s,
j = 1 to m,
i = 1 to n,
y_{ki} = amount of output k produced by DMU i,
x_{ji} = amount of input j utilized by DMU i,
u_k = weight given to output k,
u_j = weight given to input j.

The model that we apply in this study is valid for units that work under constant returns to scale. The weighted ratio of outputs to inputs will range between 0 and 1 for all the DMUs of the model.

The fractional program shown as (2) can be converted to a linear program if either the denominator or numerator of the ratio is forced to be unity. By setting the denominator of the ratio equal to unity, one can obtain the following output maximization linear programming problem for constant inputs.

$$\max \sum_{k=1}^{s} v_k y_{kp} \quad \text{s.t} \quad \sum_{j=1}^{m} u_j x_{jp} = 1 \ \ \sum_{k=1}^{s} v_k y_{ki} - \sum_{j=1}^{m} u_j x_{ji} \le 0 , \ \ \forall i \ v_k , u_j \ge 0 , \ \ \forall k, j \qquad (3)$$

The above problem is run n times in identifying the relative efficiency scores of all the DMUs. Each DMU selects input and output weights that maximize its efficiency score. In general, a DMU is considered to be efficient if it obtains a score of 1, and conversely considered inefficient if the score is less than 1.

5. Data

In this study, in order to estimate the technical efficiency index of the production process in the 31 countries of Europe for the year 2004, we apply through DEA a model with two inputs (CEI, DEI) and two outputs (GDP, CO2 emissions). For *the economy machine to 'work',* we need primary[5] energy consumption, broken down into two indexes: a) the 'dirty' energy consumption index (DEI) and b) the 'clean' energy consumption index (CEI). The DEI index is the sum of the consumption of oil (DPET), coal (DCOA), and natural gas (DNAT) while the CEI index is the sum of the

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[5] Primary energy is the energy content of the energy carriers that still has not been modified or processed.

consumption of nuclear (CNE), geothermal (CGSW) and hydro-electric (CHP) energy. The exploitation of these natural resources in the productive process, yields one 'desirable' (GDP) and one 'undesirable' output, which is the environmental pollution (CO2 emissions) (Schmalensee *et al.*1998).

An essential point regarding the inputs and outputs is that they are not specified in the traditional sense of DEA. GDP and CO2 emissions are therefore not the outputs solely due to fossil and non-fossil energy consumption. The context of the current application demands them to be interpreted as the representative outputs and inputs relevant to the calculation of the efficiency index. An analogous macro economic context of DEA applications have been described/presented in the literature (Ramanathan, 2006; Golany and Thore, 1997).

In order to treat the undesirable factor in the model, a nonlinear monotone decreasing transformation 1/b is applied to the CO2 emissions, which in this study are considered as by-product, a direct consequence of the productive process. Specifically, the undesirable[6] output (CO2 emissions), is entered as its reciprocal value (1/CO2) in the DEA model**.** The data used cover a time period of 25 years from the 1980's to the mid 2000's. For this specific time period, having studied a selected sample of European countries (out of 31) which belong to the high income group of OECD members, we can under certain circumstances estimate (*applying a procedure (Appendix B) similar to those implemented by* (*R.Ramanathan, 2006)*) the margins of long term increase or decrease in the levels of exhaustible energy resources of these countries (i.e. in 2025/2030). These estimations depend directly on the maximization of the TE index in 2025 and 2030 respectively. At the same time, we consider that a) CO2 emissions at that time *(2025 or 2030)* are maintained at the same levels as in 1990 and that b) the definition of the indexes of 'clean' energy (CEI) and GDP for the same year *(2025 or 2030)* is based on a reference case[7].

6. Empirical applications of the model

6.1 Definition of the TE index for 31 European countries by using the DEA method

In the following table (Table 1) the 31 countries of Europe are classified according to the index of technical efficiency (TE) and the per capita indexes of: GDP, environmental pollution (CO2 emissions), and energy consumption (DEI, CEI) for the year 2004. The formation of the TE index is the result of the information that it contains and concerns the intensity of the economic activity, the extent of ecological degradation, and the management of energy resources of each country.

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[6] Other methods for treating undesirable factors in DEA:

- Ignoring undesirable factors in Dea models
- Treating undesirable outputs (inputs) as inputs (outputs)
- Treating undesirable factors in nonlinear DEA model (Fare et.al., 1989)
- Using a linear monotone decreasing transformation to deal with undesirable factors (Seiford and Zhu, 2002)
- Directional distance function approach (Fare and Grosskopf, 2004a)

[7] The reference case describes what will happen if, the already observed, economic and technological tendencies continue. Aim of the reference case is to quantify the energy-economic evolution, in a way that it can prove useful as a reference point for the evaluation of alternative energy policies.

Table 1

04' Countries	TE	R TE	GDP p.c	R GDP p.c	CO2pc	R CO2 pc	CEIpc	R CEI pc	DEI Pc	R DEI Pc	POP	R POP
Albania	**0,294**	**16**	1,945	28	1,1894	1	0,0152	17	0,0175	1	3,54	27
Austria	**0,494**	**8**	24,870	10	8,5364	17	0,0489	7	0,1342	20	8,17	17
Belgium	**0,295**	**15**	23,377	13	14,266	29	0,0479	8	0,2109	29	10,35	13
Bosnia & Herzegovina	**0,077**	**29**	1,265	30	3,0387	2	0,0140	18	0,0433	2	4,35	25
Bulgaria	**0,058**	**30**	2,021	27	6,2687	11	0,0272	13	0,0921	10	7,52	18
Croatia	**0,175**	**22**	4,874	22	4,8036	6	0,0110	22	0,0737	7	4,50	24
Czech Republic	**0,112**	**25**	6,105	20	10,970	25	0,0300	11	0,1443	22	10,25	14
Denmark	**0,570**	**5**	30,684	5	10,261	22	0,0180	16	0,1434	21	5,41	21
Finland	**0,409**	**11**	25,212	9	11,789	27	0,0903	4	0,1641	27	5,21	22
France	**0,576**	**4**	23,402	12	6,7099	13	0,0836	5	0,1083	15	60,46	3
Germany	**0,414**	**10**	23,732	11	10,460	23	0,0267	14	0,1528	25	82,42	1
Greece	**0,259**	**18**	12,420	17	9,9677	21	0,0055	28	0,1275	18	10,65	11
Hungary	**0,155**	**23**	5,453	21	5,6201	8	0,0123	19	0,0937	11	10,03	15
Iceland	**0,558**	**6**	31,498	4	12,099	28	0,3414	1	0,1497	24	0,29	31
Ireland	**0,497**	**7**	29,256	6	10,694	24	0,0034	30	0,1558	26	3,97	26
Italy	**0,406**	**12**	19,182	15	8,3493	16	0,0102	24	0,1259	17	58,09	5
Luxembourg	**0,276**	**17**	47,436	1	26,621	31	0,0048	29	0,3971	31	0,46	30
FYR Macedonia	**0,094**	**27**	1,791	29	3,7472	4	0,0067	25	0,0487	4	2,04	28
Netherlands	**0,256**	**20**	23,295	14	16,361	30	0,0062	27	0,2424	30	16,32	9
Norway	**0,618**	**3**	39,146	2	11,178	26	0,2376	2	0,1687	28	4,57	23
Poland	**0,134**	**24**	4,840	23	7,4557	15	0,0008	31	0,0960	12	38,58	7
Portugal	**0,299**	**14**	10,31	19	6,027	10	0,0117	20	0,0917	9	10,52	12
Romania	**0,085**	**28**	2,098	26	4,2625	5	0,0104	23	0,0653	6	22,36	8
Serbia & Montenegro	**0,043**	**31**	0,969	31	4,8689	7	0,0112	21	0,0600	5	10,83	10
Slovakia	**0,112**	**26**	4,461	24	7,0891	14	0,0432	10	0,1056	14	5,42	20
Slovenia	**0,258**	**19**	10,782	18	9,0757	19	0,0469	9	0,1110	16	2,01	29
Spain	**0,325**	**13**	16,261	16	8,9844	18	0,0283	12	0,1332	19	40,28	6
Sweden	**0,797**	**2**	28,876	7	6,5733	12	0,1612	3	0,0965	13	8,99	16
Switzerland	**1**	**1**	33,906	3	6,0003	9	0,0824	6	0,0904	8	7,48	19
Turkey	**0,200**	**21**	3,328	25	3,0727	3	0,0067	26	0,0443	3	68,89	2
United Kingdom	**0,476**	**9**	26,187	8	9,6179	20	0,0181	15	0,1465	23	60,27	4

Source: IEA (2004), World Bank (2006).

6.2 Estimations regarding the possibilities of long-term exploitation of exhaustible energy resources in four European countries (Switzerland, Greece, United Kingdom, Luxemburg), which belong to the high income group of OECD members

In this section we take the cases of 4 countries (Switzerland, Greece, United Kingdom, and Luxembourg) that belong to the high-income OECD members and we examine them separately (Appendix B). For each country we determine the average annual percentage change of per capita GDP and per capita CEI for the period 1980-2004 and based on the reference case we evaluate the indexes (GDP and CEI) for the year 2025/2030. In order for the emission levels of CO2 (in 2025/2030) not to exceed those of 1990, we find (through DEA) the percentage change in the index of 'dirty energy consumption' (DEI) for the year 2025/2030 in relation to 2004, so as to achieve maximum efficiency for 2025/2030.

In the following analysis, it becomes obvious that the estimations of the sustainability possibilities concerning the sample of four European countries are directly connected with the significant differentiations that are being observed in the trends of the curve that expresses the course of the index of environmental pollution, as the per capita GDP is being raised (Figures 2, 3, 4, 5). The curve in question, for the time interval being studied (1980-2004), is a result of the way that the energy intensity is formed in the developed economic systems of the four countries belonging to the sample (Figure 1). The energy intensity is determined both from the degree of substitution between energy resources and the type of the substitution (i.e. whether it exists between renewable and exhaustible natural resources, or exclusively to exhaustible resources (i.e. between oil and natural gas). Therefore, the allocation between the two types of energy that each country chooses to use shapes the structure of the entire environmental and economic system that it belongs to and, thus, provides clear markings regarding the margins for long-term, smooth and sustainable economic activity.

The economic activity of developed economies of the sample of four European countries is mainly based on exhaustible energy resources, the combustion of which results in high levels of CO2 emissions. Exhaustible energy resources are the dominant but not the only form of energy exploitation, as the countries appear active in the use of renewable energy resources (Figure 1), the consumption of which does not cause environmental degradation (CO2 emissions), and therefore can guarantee long-term sustainable economic activity. The more a country turns to using more clean forms of energy, the better its TE index, calculated by the ratio of the weighted sum of outputs (total output) to the weighted sum of inputs (total input). In other words, the amelioration in quality of the total product (total output), for given levels of total energy input, is achieved when a substitution exists between the components of total energy input and more specifically when dirty energy consumption is substituted with clean energy consumption, keeping the total energy power which is necessary for the production process constant.

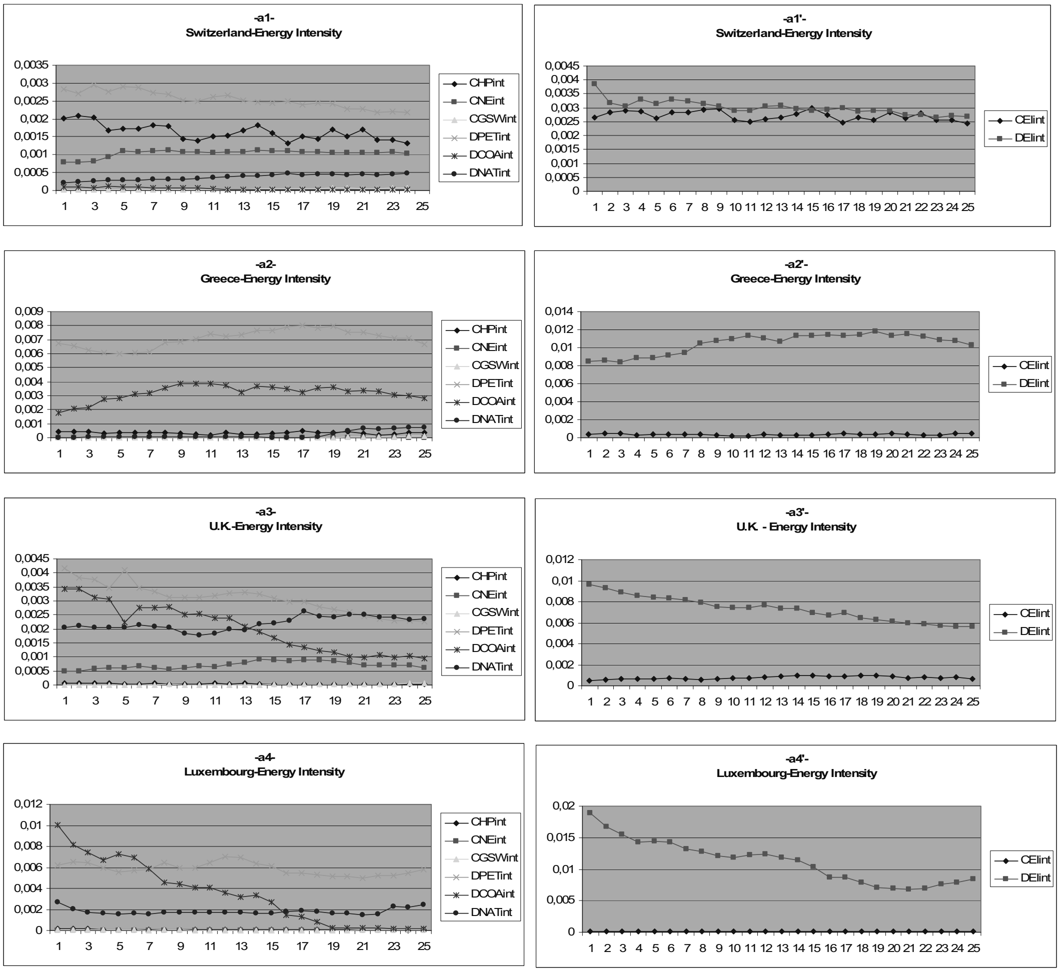
The cases of four countries

Switzerland: For the period 1980-2004 there is a gradual disengagement of Switzerland (Figure 1 -α1-) from oil consumption, which is the main form of energy exploitation in this country. A significant part of the energy power from the consumption and flare of oil, which is responsible for the larger part of CO2 emissions, is substituted mainly by the consumption of natural gas (considered to be the least polluting fossil fuel of the three). Switzerland is the only country in the sample that extensively uses hydro-electric and nuclear energy. The exploitation of these forms of energy has an advantage over natural gas and coal (the consumption of which the country is almost totally free from) (Figure 1 -α1-). Moreover, during the final decade, Switzerland is visibly trying to support the exploitation of geothermal energy, something which increases the prospective for further withdrawal from oil consumption, as the GDP production increases. The formation of the energy intensity in Switzerland during 1980-2004 is responsible for the diachronic stabilization of per capita CO2 emissions as the per capita GDP increases (Figure 2).

The over time stabilization of per capita CO2 emissions (resulting from the abovementioned) as the per capita GDP increases (Figure 2), explains the strong tendency of Switzerland to long term sustainable economic activity that clearly outweighs the rest of the countries in the sample. More specifically, the CO2 emissions assimilation capacity by the natural environment and the ensurance of stabilization of the exhaustible natural resources stock can be satisfactorily achieved by the year 2025 (→provided maximum efficiency) with an increase in the consumption limits of 'dirty energy sources' by 28,827% in relation to 2004 levels (DEI_{2025}=0,872 Quadrillion (10^{15}) Btu).

Similarly, to reach evaluations concerning the year 2030 (→provided maximum efficiency), the increase in the consumption limits of 'dirty energy sources' is about 37,100% in relation to 2004 levels (DEI_{2030}=0,928 Quadrillion (10^{15}) Btu).

Figure 1



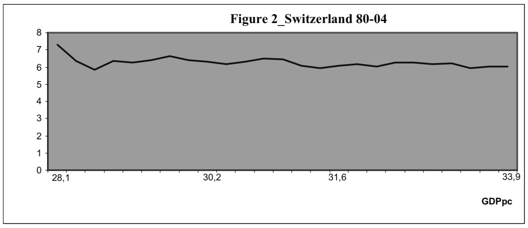
Source: Figure 1 presents the Energy Intensity Indexes, from the processing of data that were furnished by the organizations IEA (2004) and World Bank (2006).

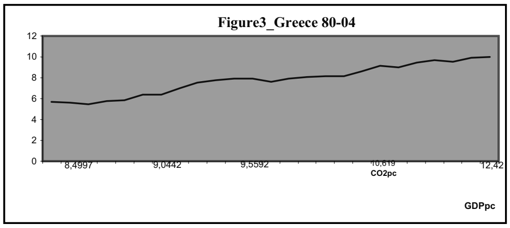
The indexes of Dirty and Clean Energy intensities: *Petroleum=DPETint, Coal=DCOAint, Natural Gas=DNATint, Nuclear Energy=CNEint, Geothermal Energy=CGSWint, Hydroelectric Energy=CHPint*

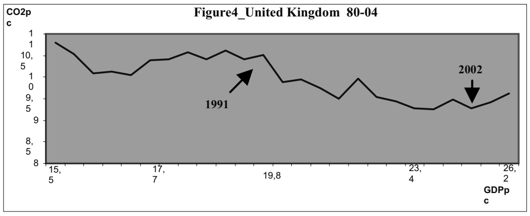
Dirty Energy Intensity=*DEIint,* Clean Energy Intensity=*CEIint*. (The *DEI* index is the sum of the consumption of *(DPET), (DCOA)* and *(DNAT)* while the *CEI* index is the sum of the consumption of *(CNE), (CGSW)* and *(CHP)).*

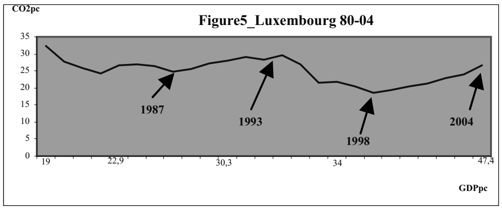
Greece: In contrast to Switzerland, Greece is one of the worst cases among high income OECD countries concerning the possibilities for long term sustainable economic activity. The diagrams in (Figure 1 -a2-) clearly show a relatively positive evolution in the last few years, mainly from 1999 onwards. As GDP production increases, the mild decline in the consumption of oil and coal is accompanied by a parallel increase in the exploitation of natural gas and geothermal power.

This tendency should be preserved and perhaps continued with an intensified pace for a prolonged period of time, until the stabilization of the per capita CO2 emissions is achieved in relation to the constantly increasing GDP per capita (Figure 3). The case on which the estimations are based for the achievement of full efficiency in 2025/2030, is determined by the behavior of the efficiency index of each country for the period 1980-2004. Resulting from the estimations concerning Greece, the index (DEI) should be reduced by 64,95% by 2025 and by 64,77% by 2030 in relation to the 2004 levels (DEI=0,4758 Quadrillion (10^{15}) Btu for 2025) and (DEI=0,4782 Quadrillion (10^{15}) Btu for 2030) so as to have a significant decrease in the average annual percentage increase of CO2 emissions (2,857% for the period 1980-2004) and be in a position to further consider possibilities of long term sustainability.









Source: The figures 2 to 5 present the results from the processing of data that were furnished by the organizations IEA (2004) and World Bank (2006), and refer to the emission indexes of CO2 and GDP respectively, and by extension to their per capita sizes (CO2pc., GDPpc.).

United Kingdom - Luxembourg: This is a typical example of the United Kingdom with continuous short-term changes in the index of environmental pollution as the per capita GDP increases. Figure 4 shows the per capita emissions of CO2 decreasing, in relation to the constantly growing GDP per capita from 1991 onwards. Such an evolution can be explained if we take into consideration the fact that CO2 emissions where classified as harmful only in the late 1980s, consequently no measurements for the protection of the environment were made until that time. This fact is also confirmed by (Figure 1 -a3-) where from the late 80's, the country's tendency to break free from the exploitation of polluting fuels (oil and coal) and to promote the less dirty natural gas is (clearly) visible.

Thus, a gradual substitution occurs between the more and the less dirty energy resources. Concurrently, the increase in the use of nuclear energy as the GDP increases implies the possibility of the substitution of the exhaustible (dirty) energy resources with the renewable (clean) energy resources. It is known that the United Kingdom is one of the countries that invest in environmental protection to ensure long term sustainable economic activity. This allows the U.K to increase the consumption of dirty energy by 0,454% by the year 2025 and by 3,563% by 2030, in relation to the 2004 levels (DEI=8,8691 Quadrillion (10^{15}) Btu for 2025) and (DEI=9,1436 Quadrillion (10^{15}) Btu for 2030).

This rate is obviously considerably lower than that of Switzerland. Consequently, the long run stabilization of the CO2 p.c index, in relation to the constantly increasing GDP p.c index, proves to be more efficient than a short-term decrease in the CO2 p.c index in relation to the GDP p.c. This finding is also confirmed in the case of Luxembourg (Figure 5), which extensively exploits natural gas, something which, combined with the better energy saving technology (as it is the European country with the highest per capita GDP investing in research and technology), can justify the huge decrease in coal consumption as well as the slight decrease (the final decade) in the consumption of oil as the GDP increases. The fact that the structure of the energy system of Luxembourg is still based on exhaustible energy resources implies short term alternations of the index of environmental pollution, as the per capita GDP is being raised, something which hinders the diachronic stabilization of the environmental degradation levels (CO2 emissions). As the study reveals**,** the consumption of ‘dirty’ energy should be decreased by 12,65% by 2025 and increased by 0,647% by 2030, in relation to 2004 levels -(DEI=0,1605 Quadrillion (10^{15}) Btu for 2025) and (DEI=0,1849 Quadrillion (10^{15}) Btu for 2030)- to achieve full efficiency by 2025 and 2030, respectively. In the case of Luxembourg, the differentiation between the years 2025 and 2030 is attributed to: a) the effort towards, and significant development in a controlled increase of the average annual percentage change of CO2 emissions for the period 1980-2004 and b) the enlargement of the time horizon by 5 years, which ensures the better assimilation of the country’s energy policy measures.

From the behavior of the curve of the U.K (Figure 4), this descending line is reversed from 2002 onwards. Something similar is observed in Luxembourg (Figure 5), where the per capita CO2 emissions index increases as the GDP p.c increases, for the periods 1987-1993 and 1998-2004.

Thus far, our analysis has proved that the countries which invest in a) renewable energy resources e.g. Switzerland (CHP, CNE) and the United Kingdom (CNE) and in b) less polluting fossil fuel (DNAT), ensure better prospects for sustainable economic activity, since their energy policy, which, combined with the new technologies of energy saving that they adopt, attempts not only a controlled increase in the index of CO2 emissions but also its stabilization through time. Regarding the cases of Greece and Luxemburg, countries still depending largely on fossil fuels, Luxemburg has the comparative advantage, as it aims to gradually disengage from the consumption of more polluting fossil fuels (oil, coal), through further exploitation of natural gas.

The greater the convergence between the indexes of dirty (DEIint - with a downward trend) and clean (CEIint - with an upward trend) energy intensity (Figure 1 –a1’-, -a2’-, -a3’-, -a4’-), the wider the margins of long term sustainable economic activity.

Clearly the aim of every developed economy is the gradual decrease of CO2 p.c in relation to the constantly growing GDP p.c. However, in order for the economic systems to cope with such a challenge, first and foremost the long run stabilization of per capita CO2 emissions must be ensured.

7. Conclusions

In the present study DEA is employed to develop an efficiency index (TE) for the simultaneous analysis of the interrelationships among CO2 emissions, energy consumption and GDP of the production process in the economic systems of European countries. The TE index, which is defined as the ratio of the weighted sum of outputs to the weighted sum of inputs, functions as an efficiency measure of the production process in the countries of Europe. The degree of efficiency is specified by the convergence of the quantitative increase and the qualitative improvement of the product (total output).

The amelioration in quality of the total product, for given levels of total energy input, is achieved when a substitution is made between the components of total energy input and more specifically between dirty and clean energy, while keeping constant the total energy power which is necessary for the production process. In other words, the amelioration in quality of the total product (total output) is a result of the way that the energy intensity in European countries is formed. The qualitative improvement of the product can guarantee both the stabilization of environmental degradation through the controlled exploitation of fossil fuels and therefore better prospects for long-term sustainable economic activity.

In this study Data Envelopment Analysis (DEA) is further used to estimate the margins of long term increases or decreases in the exhaustible energy resource consumption levels of a selected sample of European countries (Switzerland, United Kingdom, Greece, Luxembourg). The evaluation of possibilities for sustainable economic development that concern the sample of the four European countries, is directly connected with the significant differentiations that are observed in the trends of the environmental pollution index, as the per capita GDP is raised. These trends are described as follows:

- Stabilizing trend in the per capita CO2 emissions, as the per capita GDP is raised [Case of Switzerland – the best possible]
- Upward course of the environmental degradation index, as the per capita GDP is raised [Case of Greece – the worst]
- Continuous short-term alternations of short time intervals of the environmental degradation index, as the per capita GDP is raised [Case of United Kingdom – intermediate tending towards that of Switzerland]
- Continuous short-term alternations of greater time intervals of the environmental degradation index, as the per capita GDP is raised [Case of Luxemburg - intermediate tending towards that of Greece].

The curve in question, for the time interval that was studied (1980-2004), is a result of the way that the energy intensity of the developed economic systems of the four countries of the sample was modulated. The energy intensity is determined both by the degree of substitution between energy resources and the kind of substitution (i.e. whether the substitution exists between renewable and exhaustible natural resources or exclusively among exhaustible resources). Consequently, the method by which every country takes advantage of its energy sources shapes the infrastructure of the entire environmental-economic system that it belongs to, and therefore provides clear indications of the margins for long-term, smooth and sustainable economic activity.

The more a country abstains from the consumption and flaring of fossil fuels (through the gradual substitution of dirty with clean energy), the greater the convergence of the quantitative increase and the qualitative improvement of the product, since the maximization of the desirable output (GDP) is accompanied by the diachronic stabilization of the undesirable byproduct (CO2 emissions) and therefore the preservation of exhaustible natural resources stock.

Through the analysis above, when a European country is unleashed from the consumption of a 'dirty energy resource' like oil, coal or natural gas, wider margins for assimilation of the emitted Carbon Dioxide by the environment are ensured. In this way the country actively participates as an isolated unit in the global effort to deal with the ecological degradation.

Moreover, when a significant disengagement from a dirty energy resource exists for all the developed economies, not only in Europe but in the whole world as well, there is hope for a stabilization through time of i) a significant part of the exhaustible resources stock and ii) the environmental degradation since the per capita GDP increases. Therefore, the way that the energy system is structured - based on substitution relations between the more and the less 'dirty' fossil fuels, as well as the renewable and exhaustible energy resources - is considered to be vital in ensuring the necessary margins of a sustainable economic activity.

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Appendix A

1. European Countries

The 31 European countries studied are as follows:

Albania (L.M.I), Austria (H.I OECD), Belgium (H.I OECD), Bosnia & Herzegovina (L.M.I), Bulgaria (U.M.I), Croatia (U.M.I), The Czech Republic (H.I OECD), Denmark (H.I OECD), Finland (H.I OECD), France (H.I OECD), Germany (H.I OECD), Greece (H.I OECD), Hungary (U.M.I), Iceland (H.I OECD), Ireland (H.I OECD), Italy (H.I OECD), Luxembourg (H.I OECD), FYR Macedonia (L.M.I), The Netherlands (H.I OECD), Norway (H.I OECD), Poland (U.M.I), Portugal (H.I OECD), Romania (U.M.I), Serbia & Montenegro (U.M.I), Slovakia (U.M.I), Slovenia (H.I nonOECD), Spain (H.I OECD), Sweden (H.I OECD), Switzerland (H.I OECD), Turkey (U.M.I), The United Kingdom (H.I OECD).

L.M.I = Lower Middle Income
U.M.I = Upper Middle Income
H.I OECD = High Income OECD
H.I nonOECD = High Income non OECD
Source: World Bank (2006)

Data availability for Former Yugoslavia and Former Czechoslovakia:

- Former Yugoslavia: 1980-1991 Bosnia and Herzegovina, Croatia, FYR Macedonia, Serbia and Montenegro, Slovenia: 1992-2004
- Former Czechoslovakia: 1980-1992 Czech Republic, Slovakia: 1993-2004

The European countries which we have chosen are based on:

a) the geographical classification according to the *World Bank (2006)* (source for the index of economic development) and the *Energy Information Administration EIA (2004)* (source for the index of energy consumption and environmental pollution) and b) the data availability of the four index categories of the countries examined for the period 1980-2004.

2. Indexes

a) GDP

We refer to real Gross Domestic Product (GDP)
Units: Current US$ adjusted to 2000 base (billions of 2000 dollars)
Source: World Bank-World Development Indicators (2006)

b) DEI-CEI

Total primary energy consumption includes the consumption of petroleum, dry natural gas, coal, hydroelectric, nuclear, and geothermal, solar and electric wind power. Total primary energy consumption for each country also includes net electricity imports. This is because the net electricity consumption by energy type data, are in fact net electricity generation data that have not been adjusted to include electricity imports and exclude electricity exports.
Units: Quadrillion (10^{15}) Btu
Source: EIA (Energy Information Administration)-International Energy Annual (2004)

c) CO2 emissions

Total carbon dioxide emissions from the consumption and flaring of fossil fuels, measured in million metric tons of carbon dioxide, include carbon dioxide emissions from: the consumption and flaring of petroleum, coal and natural gas.

Source: EIA (Energy Information Administration) International Energy Annual (2004)
Among the 6 gases responsible for the green house effect (CO2: Carbon Dioxide, CH4: Methane, N2O: Nitrous Oxide, HFCs: Hydrofluorocarbons, PFCs: Perflourocarbons, SF6: Sulfur Hexafluoride), we chose to introduce CO2 (having the highest emission levels compared to the other gases) in the model as a representative index of environmental pollution.

Greece

T	GDP	CO2	DEI	CEI	TE
1980	84,00	54,63	0,714330	0,0353	**0,990**
1981	82,70	54,92	0,710607	0,0355	**0,980**
1982	**81,76**	**53,37**	**0,688563**	**0,0371**	**1,000**
1983	80,88	56,67	0,716798	0,0245	**0,938**
1984	82,50	58,17	0,730008	0,0298	**0,947**
1985	84,57	62,99	0,776581	0,0292	**0,914**
1986	85,01	63,73	0,799260	0,0337	**0,897**
1987	83,09	69,78	0,866601	0,0289	**0,807**
1988	86,65	74,88	0,933160	0,0244	**0,779**
1989	89,95	78,20	0,981229	0,0197	**0,765**
1990	89,95	80,45	1,018046	0,0182	**0,736**
1991	92,74	81,07	1,022298	0,0320	**0,768**
1992	93,39	78,78	0,994389	0,0240	**0,789**
1993	91,89	82,41	1,044667	0,0246	**0,740**
1994	93,73	83,94	1,058815	0,0276	**0,748**
1995	94,64	85,03	1,084732	0,0374	**0,742**
1996	96,87	85,80	1,093856	0,0460	**0,756**
1997	100,39	90,27	1,150886	0,0407	**0,743**
1998	103,77	95,98	1,228089	0,0398	**0,720**
1999	107,32	94,72	1,215939	0,0500	**0,755**
2000	112,13	100,28	1,294480	0,0432	**0,740**
2001	116,90	102,26	1,315721	0,0307	**0,755**
2002	121,30	101,52	1,312525	0,0367	**0,788**
2003	126,95	105,29	1,369223	0,0606	**0,795**
2004	132,24	106,13	1,357357	0,0583	**0,835**

Source: IEA (2004), World Bank (2006)

Appendix B

Switzerland

T	GDP	CO2	DEI	CEI	TE
1980	179,88	46,62	0,6918	0,4750	**0,739**
1981	182,72	41,03	0,5787	0,5154	**0,927**
1982	180,10	37,95	0,5495	0,5220	**1,000**
1983	181,01	41,50	0,5976	0,5203	**0,897**
1984	186,49	41,04	0,5885	0,4898	**0,914**
1985	192,86	42,20	0,6360	0,5483	**0,884**
1986	196,00	44,14	0,6365	0,5583	**0,876**
1987	197,44	42,61	0,6196	0,5802	**0,921**
1988	203,58	42,53	0,6206	0,5993	**0,941**
1989	212,42	42,00	0,6184	0,5418	**0,952**
1990	220,37	43,36	0,6351	0,5507	**0,941**
1991	218,61	45,02	0,6641	0,5652	**0,893**
1992	218,33	45,24	0,6701	0,5756	**0,887**
1993	217,28	43,14	0,6421	0,6046	**0,944**
1994	218,44	42,36	0,6325	0,6529	**0,980**
1995	222,66	43,53	0,6504	0,6124	**0,946**
1996	223,82	44,59	0,6668	0,5512	**0,902**
1997	228,09	43,43	0,6518	0,6033	**0,955**
1998	234,46	45,29	0,6803	0,6015	**0,920**
1999	237,54	45,59	0,6859	0,6719	**0,936**
2000	246,05	44,96	0,6725	0,6457	**0,971**
2001	248,61	45,53	0,6826	0,6991	**0,972**
2002	**249,42**	**43,95**	**0,6602**	**0,6354**	**1,000**
2003	248,54	44,72	0,6722	0,6373	**0,977**
2004	253,76	44,91	0,6769	0,6164	**0,976**

United Kingdom

T	GDP	CO2	DEI	CEI	TE
1980	872,14	608,30	8,3831	0,457673	**0,867**
1981	861,05	593,69	8,0420	0,474231	**0,923**
1982	876,54	568,86	7,8241	0,547458	**0,990**
1983	909,39	570,90	7,7909	0,614824	**0,996**
1984	931,66	566,88	7,8309	0,620148	**1,000**
1985	966,91	588,25	8,0527	0,682019	**0,945**
1986	1007,61	591,23	8,2199	0,665491	**0,926**
1987	1052,23	602,53	8,3701	0,638841	**0,897**
1988	1106,60	595,42	8,2819	0,725745	**0,923**
1989	1129,95	608,00	8,4290	0,819938	**0,894**
1990	1137,39	598,48	8,4273	0,809818	**0,907**
1991	1120,71	606,55	8,5721	0,893173	**0,881**
1992	1121,52	571,86	8,2396	0,974882	**0,967**
1993	1147,63	577,69	8,4074	1,113785	**0,943**

1994	1197,98	567,26	8,3585	1,126419	**0,968**
1995	**1233,52**	**555,00**	**8,2790**	**1,125266**	**1,000**
1996	1266,69	584,01	8,8093	1,180742	**0,902**
1997	1308,38	560,67	8,4556	1,234271	**0,978**
1998	1349,20	557,35	8,4375	1,267855	**0,989**
1999	1386,96	550,20	8,4935	1,225891	**0,997**
2000	1438,28	551,02	8,5493	1,108244	**0,993**
2001	1471,39	566,16	8,6296	1,154986	**0,964**
2002	1497,41	555,29	8,5252	1,147718	**0,995**
2003	1530,27	566,46	8,6564	1,211457	**0,966**
2004	1578,28	579,68	8,8290	1,093179	**0,932**

Luxemburg

T	GDP	CO2	DEI	CEI	TE
1980	6,93	11,77	0,13107	0,00119	**0,556**
1981	6,89	10,12	0,11526	0,00134	**0,721**
1982	6,97	9,48	0,10849	0,00122	**0,801**
1983	7,17	8,88	0,10210	0,00121	**0,899**
1984	7,62	9,80	0,10983	0,00128	**0,781**
1985	7,84	9,90	0,11226	0,00109	**0,749**
1986	8,45	9,70	0,11154	0,00121	**0,782**
1987	8,65	9,16	0,11005	0,00149	**0,850**
1988	9,54	9,64	0,11531	0,00146	**0,788**
1989	10,48	10,24	0,12393	0,00113	**0,695**
1990	10,71	10,72	0,13055	0,00106	**0,637**
1991	11,37	11,29	0,14041	0,00124	**0,584**
1992	11,88	11,13	0,14057	0,00102	**0,586**
1993	12,91	11,79	0,14705	0,00107	**0,548**
1994	13,45	10,87	0,13934	0,00161	**0,638**
1995	13,94	8,83	0,12081	0,00141	**0,861**
1996	14,40	9,02	0,12494	0,00102	**0,802**
1997	15,60	8,61	0,12287	0,00132	**0,877**
1998	**16,67**	**7,95**	**0,11838**	**0,00170**	**1,000**
1999	17,98	8,42	0,12529	0,00152	**0,913**
2000	19,60	8,94	0,13228	0,00202	**0,858**
2001	19,91	9,41	0,13898	0,00221	**0,794**
2002	20,40	10,37	0,15654	0,00198	**0,660**
2003	20,99	10,96	0,16498	0,00168	**0,604**
2004	21,95	12,32	0,18374	0,00221	**0,514**

The process that we apply in order to draw estimations regarding the sustainability possibilities of the 4 countries is as follows: → The performance of the countries for the year (2025 or 2030) is included in the table for each country as a new 'DMU'. → We use GDP, CEI data for year (2025/2030) from the reference case. → We consider that CO2 emissions at that time are equal to the emissions for the reference case year 1990.

In the beginning, in order to run the program we assigned an arbitrarily high value for the fossil fuels consumption index (DEI), so that at first, the studied country appeared as inefficient (in 2025 or 2030 respectively). Then we gradually reduced the value that we set until the point that the country showed full efficiency (with TE=1) in 2025 or 2030 respectively, and simultaneous inefficiency (from 1,000 to 0,999) for the year that rendered it fully efficient before the introduction of the additional 'DMU'.