ENERGY USE AND CO_2 EMISSIONS IN PORTUGAL

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ABSTRACT

Current energy production and use patterns rely heavily on the burning of fossil fuels. This means that the world is using mainly energy sources which inevitably produce CO_2 emissions, a key factor in the greenhouse effect and of the 'resulting' climate change problem.

One of the main aims of this work is to contribute to strengthen the level of general awareness of the complex interactions between energy, economic and environmental issues, summarizing and synthesising information in a way that can help policy makers to make better-informed decisions.

For this a particular kind of analytical tool will be used – input-output analysis. Accordingly, and to illustrate some of the potentialities of the proposed "energy-economy-environment input-output model" through a specific case study, an extended input-output empirical application is implemented and developed, from which is assessed the (sectoral and aggregate) production of CO_2 emissions (derived from fossil fuels use) in Portugal.

Keywords: Input-output analysis; Energy intensities; CO2 emissions; Elasticity; Portugal

1. Introduction

1.1 Objectives

One of the main aims of this study is to explore the links between energy, economy and environment from different angles, but always with a policy-oriented focus. This will be done by implementing and developing an input-output model with satellite accounts, to analyse the links between the different economic sectors, energy production and use, and the 'corresponding' production of CO_2 emissions in Portugal.

For this, the paper is organised as follows. In Section 2, there will be presented a brief outline of the basic input-output model, and then succinctly discussed the core aspects of its extensions for the consideration of environmental and energy issues. In Section 3, there will be presented the data sets used for the Portuguese case, and then an extended input-output empirical application, from which is assessed the (sectoral and aggregate) production of CO_2 emissions (derived from fossil fuels use) by the Portuguese economy. There will be also offered a succinct reflection on the use of elasticities of CO_2 emissions with some of the model parameters, as measures of sensitivity analysis of the level of emissions. Accordingly, a summary of the key lessons learned and a discussion of their policy relevance will be offered in Section 4.

1.2 Historical Background

For analysing possible energy futures and designing new policies it is useful to present some background information about the current state and recent trends of the Portuguese energy system. Accordingly, there will be presented a brief overview of the role and importance of energy in Portugal (contextualized within the European Union), and how it has been developing through the last decade[1], as well on the importance of CO_2 emissions in the current political debate (in the context of the Kyoto Protocol).

To start with, it is crucial to note that since Portuguese accession to the European Union (in 1986), its environmental and energy policies reflect the principles, aims and actions of the corresponding European policies. Accordingly, it comes as no surprise that trade-offs among three objectives – energy security, environmental protection, and economic growth – have been dominant concerns in Portuguese energy policy making for the last three decades, though they have been pursued with changing emphasis, depending on the historical situation and emerging issues and constraints. For example, one can say that after the Portuguese accession to the European Union (1986), and increasingly over the 1990s, although energy security concerns has by no means disappeared, it has lost considerable weight to competitiveness, and at a slower rate to environmental concerns (mainly the climate change problem).

Concerning some of the 'progress' made in the energy area over the last decade, it can be emphasized that:

- Portugal has a small energy market, of around ten million inhabitants, and has the lowest *per capita* energy consumption in the European Union (thought it has been growing at considerably higher rates than GDP *per capita*).
- Primary and final energy intensities present a worrying upward trend. Moreover, concerning absolute energy intensity levels, Portugal presents a situation clearly unfavourable compared to the European Union average.
- Portugal does not have its own fossil energy resources but it has a structure of consumption that is based on oil products; therefore, the country imports most of the energy consumed.
- The limited domestic energy resources produced in Portugal are renewables, such as hydropower and biomass. Indeed, the hydroelectric component is significant in the Portuguese electricity system.

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[1] It is worth mentioning that the International Energy Agency releases annually a review analysing energy policies and energy market developments in its Member Countries, which include the EU Member States (e.g. IEA/OECD, 2000b). Furthermore, the European Environment Agency has produced several reports which generally contain detailed data and analysis concerning, among others, environmental and energy issues, for each of the European Union Member States (e.g. EEA, 1998, 1999, 2000 and 2002b). Concerning Portugal, reference can be made to DGE/ME (2002) and IEA/OECD (2000a). Thus, these works are recommended for those who are interested in a more exhaustive analysis than that presented here.

Moreover, it is also essential to take into consideration that, under the terms of the European Union allocation agreement (the 'burden sharing' system), Portugal may fulfil its Kyoto commitments by limiting its increase of greenhouse gases emissions to 27 per cent above 1990 levels over the period 2008-2012. Concerning CO_2 emissions, the limit for its increase is 40 per cent. This latter 'Kyoto target' is the focus of our interest, though restricted to the consideration of the CO_2 emissions that result from the combustion of fossil fuels. From some historic data concerning emissions it is relevant to call attention that:

- In the year 2000, CO_2 emissions contributed to 74.6 per cent of total Portuguese greenhouse gases emissions. Moreover, from 1990 to 2000, CO_2 emissions increased 43.6 per cent, which means that the limit of 40 per cent increase for 2008-2012 was already passed in the year 2000.
- CO_2 emissions that result from fuel combustion represented 90-91 per cent of the total CO_2 emissions produced in the 1990s, and from 1990 to 2000, CO_2 emissions from fossil fuel burning increased 44.5 per cent.

From all this results that presently the 'Kyoto target' for Portuguese CO_2 emissions is not any more 'to control the growth', but rather to reverse the current trend and therefore 'to reduce' present CO_2 emissions. Thus, more than ever, it is manifest that CO_2 emissions are of foremost importance in the current political debate in Portugal. Accordingly, measures to reduce energy-related greenhouse gas emissions, and specially CO_2 emissions, are clearly one of the biggest challenges for energy policy makers.

2. The input-output framework

In an input-output approach the economic structure is defined in terms of sectors. It can be said that the relative simplicity of such a systematic connection of a set of economic variables provides a modelling framework suitable for calculating economic impacts (over all of the economy) of several human activities.

2. 1. The basic input-output model[2]

The basic principle of input–output analysis states that each sector's production process can be represented by a vector of structural coefficients that describe the relationship between the inputs it absorbs and the outputs it produces[3].

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[2] The basic concepts of input-output analysis were discussed in detail by Wassily Leontief in the 1960s (Leontief, 1966), and more recently by Miller and Blair (1985), and Proops et al. (1993).

[3] General assumptions of the basic input-output model are: homogeneity (i.e. each sector or industry produces a single product) and linear production functions (which implies proportionality of inputs with outputs in each sector and excludes both the possibility of economies or diseconomies of scale, and of substitution between production factors).

As the total output (production) of a sector i (X_i) can be delivered for intermediate or for final demand, an output equation may be defined by:

$$X_i = \sum_j x_{ij} + Y_i \qquad (1),$$

where the element x_{ij} represents the 'value' of input from sector i to sector j (where i represents the number of the row and j the number of the column), and Y_i represents the total final demand for sector i (which includes production for consumption (of households and governments), investment purposes (fixed capital formation, changes in stocks) or exports).

Considering constant returns to scale, the output (or supply) equation of one generic sector becomes:

$$X_i = \sum_j a_{ij} X_j + Y_i \qquad (2),$$

where the coefficients a_{ij}, defined as the delivery from sector i to j per unit of sector's j output, are known as the 'technical' or 'technological coefficients'.

To represent the nation's productive system, we will have a system of n (linear) simultaneous equations, each one describing the distributions of one sector's product through the economy. As the algebraic manipulation of such a system is very complex, it is useful to use its representation in matrix (condensed) form[4]:

$$\mathbf{Ax} + \mathbf{y} = \mathbf{x} \qquad (3),$$

where $\mathbf{A}$ is the matrix of the technological coefficients, $\mathbf{y}$ is the vector of final demand, and $\mathbf{x}$ is the vector of corresponding total outputs.

Using the basic concepts of matrix algebra, with $\mathbf{I}$ as the unit matrix, expression (3) can be reorganized, to give:

$$\mathbf{x} = (\mathbf{I}\text{-}\mathbf{A})^{-1}\mathbf{y} \qquad (4).$$

This expression is the fundamental matrix representation of input-output analysis, and the inverse matrix $(\mathbf{I}\text{-}\mathbf{A})^{-1}$ is known as the 'Leontief inverse matrix' (or also as the 'multiplier matrix').

By decomposing equation (4) (which can be seen as the result of an iterative process that shows the progressive adjustments of output to final demand and input requirements), one can separate out the direct from the indirect requirements for production in the economy, which are necessary to satisfy a certain vector of final demand commodities (Gay and Proops, 1993: 115-116):

$$\mathbf{x} = \mathbf{y} + \mathbf{Ay} + \mathbf{A}^2\mathbf{y} + \ldots + \mathbf{A}^t\mathbf{y} + \ldots \qquad (5).$$

So, as Proops et al. (1993: 112) point out, we can decompose the total demand for the n goods produced in the economy as follows:

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[4] Notational conventions: upper case bold letters are used to denote matrices, and lower case italic letters with subscript indices to denote its elements; lower case bold letters are used to denote vectors, and upper case italic letters with subscript indices to denote its elements; and lower case italic letters are used to denote scalars.

• **y** is required for final demand. This is the direct effect.

• **Ay** is the production necessary to allow the production of a final demand vector, **y**. This is the 'first-round indirect effect'.

• $\mathbf{A}^t\mathbf{y} = \mathbf{A}(\mathbf{A}^{t-1}\mathbf{y})$ is needed to produce the goods $\mathbf{A}^{t-1}\mathbf{y}$. This is the '$t^{th}$-round indirect effect'.

Clearly, the total indirect effects (or intermediate demand) are the sum of the first-round, second-round, etc. (Gay and Proops, 1993: 115-116).

2. 2. Extensions of the basic model to account for energy-economy-environment interactions

Having established the basic input-output framework, it is time to move on to discuss some extensions of this technique, in order to make particularly explicit the link between the level of economic activity in a country, its corresponding impact on the environment, and/or the corresponding energy interactions.

Extensions of the application of input-output models to the examination of interactions between economic activity and environmental issues date back to the late 1960s and early 1970s[5]. These studies can be considered as benchmarks of an approach that would be further developed by some energy analysts during the 1970s and the 1980s, extending the use of input-output analysis to consider energy-economy interactions[6].

But, over time, the modelling approaches have become more and more complex, to allow, for example, the consideration of global environmental issues such as the greenhouse effect and the 'resulting' climate change problem. This has led to the development of numerous theoretical models and empirical studies that combine both perspectives, making it hard to distinguish between environment and energy models, and therefore it become usual to talk about 'energy-economy-environment' models (Faucheaux and Levarlet, 1999: 1123).

Thus, it is not surprising that also the input-output models have been extended to deal with both environmental and energy issues. Therefore, in this section, it is intended to illustrate some of the potentialities of the energy-economy-environment models, applying the input-output technique to the structural analysis of energy requirements and CO_2 emissions by economies, relating this pollution with the use of fuels. This will be done using an approach very similar to the one used by Gay and Proops (1993) and Proops et al. (1993)[7].

To start, it is important to note that we need to introduce two kinds of distinctions into the analysis:

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[5] Detailed surveys of environmental input-output models, with many references, including theoretical extensions and applications are provided, for example, by: Hawdon and Pearson (1995), Miller and Blair (1985, Chapter 7), Richardson (1972: Chapter 11), Victor (1972: Chapter 2).

[6] Detailed surveys of energy input-output analysis are presented, for example, by: Miller and Blair (1985, Chapter 6), and Casler and Wilbur (1984).

[7] The basic concepts and explanations of the method to apply here have been discussed in detail by Proops et al. (1993: Chapter 8). Therefore, the main equations and explanation of its contents will just be restated briefly.

1. The division of the fossil fuel use, and the corresponding pollution emissions, into what concerns energy directly demanded by household consumers (for lighting, cooking, heating/cooling, transport, etc.), and energy (directly and indirectly) demanded by industrial and agricultural producers of goods to 'power' the production process (Proops, 1988: 202). The former will be designated as 'direct consumption demand' and the latter as (direct plus indirect) 'production demand'.
2. The distinction between various forms of primary (fossil) fuels[8], namely solid (coal), liquid (oil) and gaseous (natural gas), since they have different pollution emissions per unit mass, and per unit of energy delivered.

Accordingly, it is considered in this model that the total (primary) energy requirements by an economy (given by the 3-vector **f**) can be considered as the sum of the production energy requirements (given by the 3-vector [$\mathbf{f_{ind}}=\mathbf{C}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}$]), and final demand energy requirements (given by the 3-vector [$\mathbf{f_{dem}}=\mathbf{PHy}$]), i.e.:

$$\mathbf{f} = \mathbf{C}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y} + \mathbf{PHy} \qquad (6)$$[9],

where: **C** is a (3xn) matrix, whose generic element (c_{fi}) represents the (physical) quantity of fuel f used by sector i per unit of total output (i.e. the 'energy intensities corresponding to direct production demand'); **P** is a (3xn) matrix, which has only three non-zero elements, one for each fuel type, expressing the (physical) quantity of fossil fuel use per unit of final demand (i.e. the 'energy intensities corresponding to direct consumption demand'); and **H** is a (nxn) diagonal matrix, with only three non-zero elements, which are the ratios of the sum of 'final consumption of households' and 'collective consumption', to total final demand, for the three fossil fuel sectors[10].

Correspondingly, it is considered in this study that the total CO_2 emissions by an economy (given by the scalar c) can be considered as the sum of the production CO_2 emissions [$c_{ind} = \mathbf{e}'\mathbf{C}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}$] and final demand CO_2 emissions [$c_{dem} = \mathbf{e}'\mathbf{PHy}$][11], that is:

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[8] Applying an input-output approach to fuel use, as it is the case, "only primary fuels need be consider directly", since the use of secondary fuels is "dealt with automatically within the interindustry demand structure" (Gay and Proops, 1993: 116). This means that the manufacture of secondary fuels (such as, e.g. electricity or gasoline) should be ignored in the main calculation of CO_2 emissions so that double counting is avoided (IPCC, 1996).

[9] This expression is also the result of some considerations, namely: n activity sectors; three types of fossil fuels: natural gas, coal and oil; and the assumption that the use of fossil fuels by any sector is proportional to the total output from that sector.

[10] The final demand for fossil fuels corresponding to investment is not used (burnt), and consequently do not correspond to CO_2 emissions. Furthermore, the final demand for fossil fuels corresponding to exports, as these fuels leave the country concerned, are used elsewhere and therefore does not corresponds to domestic CO_2 emissions. Thus, as interest is directed towards only those fuels which were burnt (Proops et al., 1993: 154), there is need to consider only the final consumption ('final consumption of households' plus 'collective consumption'). Accordingly, we can 'modify' the final demand vector (**y**) to 'exclude' the investment and export components, by premultiplying it by a suitable (nxn) scaling matrix, **H**, and therefore using a modified final demand vector (**Hy**).

[11] For reasons of completeness, other minor sources of CO_2 emissions – other then fossil-fuel burning – should have been included in the analysis. Proops et al. (1993) do this in their analysis. However, in this specific study, and because of a lack of detailed information for Portugal, the production of CO_2 emissions from non-fuel sources will not be covered, which can be considered as a shortcoming of this work.

$$c = \mathbf{e'C(I\text{-}A)^{-1}y} + \mathbf{e'PHy} \Leftrightarrow c = [\mathbf{e'C(I\text{-}A)^{-1}} + \mathbf{e'PH}]\ \mathbf{y} \qquad (7)^{12},$$

where **e'** is the transpose of a 3-vector, **e**, whose generic element (e_f) represents the amount of CO_2 emission per unit of fuel *f*.

Furthermore, we can decompose the total CO_2 emissions as the result of an iterative process that shows CO_2 emissions progressive adjustments to final demand and fossil fuel requirements:

$$c = [\mathbf{e'PHy} + \mathbf{e'Cy}] + [\mathbf{e'CAy} + \mathbf{e'CA^2y} + \ldots + \mathbf{e'CA^{t-1}y} + \ldots] \qquad (8),$$

where (**e'PHy**) represents the CO_2 emissions attributable to direct consumption demand for fossil fuels, while (**e'Cy**) represents the CO_2 emissions attributable to direct, and the sum of all the others [$\mathbf{e'}(\mathbf{CA}+\mathbf{CA}^2+\ldots)\mathbf{y}$] to indirect production demand.

2. 3. The 'attribution' of the energy requirements and CO_2 emissions

Equations (6) and (7) make clear that both the energy requirements and the total CO_2 emissions produced by an economy can be attributed to total final demand for goods and services (represented by the final demand vector, **y**). This can be particularly useful for policy analysis purposes, as this ultimately imputes all fossil fuel use and CO_2 emissions to households' purchases.

Moreover, according to the 'components' of the final demand considered, it is possible to distinguish energy requirements and CO_2 emissions attributable to domestic consumption, from that attributable to exports, as well as to estimate the levels of energy and CO_2 emissions 'embodied' in the country's imports. It is then possible to estimate primary energy and CO_2 emissions 'embodied' in a country's international trade, as well as the country's 'responsibility' for CO_2 emissions (i.e. the CO_2 emissions attributable to consumption by a country's economy, whether arising from domestic or from foreign goods and services), and the CO_2 emissions produced by the country's economy (i.e. the CO_2 emissions attributable to the production made in the country's economy, whether demanded by national or by foreign final consumers and industries)[13].

Such an exhaustive analysis of the energy requirements and CO_2 emissions attributable to the different 'components' of the final demand was performed elsewhere for the Portuguese case (Cruz, 2002a). Here, as the interest is on the analysis of the accomplishment of the Portuguese CO_2 emissions target established under the Kyoto Protocol, we shall concentrate on the appraisal of the

[12] If we use **ê** (where **ê** is a (3x3) matrix, with the vector **e** on the diagonal) instead of **e'**, the fuel sources fundamentally responsible for CO_2 emissions are explicitly identified, since a vector of pollution intensities for each of the fuels combusted in the economy is estimated. If we use **e'**, as is the case here, then the scalar of pollution obtained represents pollution intensities for the total fuels burnt.

[13] Also, it is important to recall that what is considered in the input-output table is the domestic output by sector (i.e., imports are excluded); therefore, the energy requirements and 'consequent' CO_2 emissions correspond to goods and services produced in the country.

CO_2 emissions attributable to the production made in the Portuguese economy (and therefore released on Portuguese territory)[14].

2. 4. The elasticities of CO_2 emissions with the model parameters

According to the modelling framework presented above, the CO_2 emissions were seen to be dependent upon: the structure of final demand (i.e. the elements of vector **y**); the fuel use coefficients (i.e. the elements of matrices **C** and **P**); the structure of inter-industry relations (i.e. the elements of matrix **A**); etc. Moreover, it was assumed that these parameters are known and constant.

In this section, there will be analysed the study of the sensitivity of the level of CO_2 emissions to changes in these parameters and variables, namely through the usual measure of sensitivity used by economists – elasticity[15]. There are two main kinds of purpose behind the performance of this sensitivity analysis. On the one hand, as interest is in identifying policies that may reduce CO_2 emissions, one may consider how changing these parameters may be effective in achieving this aim. On the other hand, as the data used is not perfectly known, this analysis can provide a guide to which components of the data set need to be collected most accurately.

However, the number of elasticities that may be calculated using this study's data set is colossal. As there is need to condense information, so that it can be comprehended and thus allow policy conclusions to be drawn, there will be considered 'only' the final demand, fuel use and intermediate trading elasticities of the CO_2 emissions produced by a country's economy. This will be done using an approach very similar to the one presented by Proops et al. (1993: Section 8.5) and Cruz (2002c), which should be seen by those interested in deeper insights into the subject. Thus, what follows is no more than a brief restatement of the mathematical analysis presented in those works in order to make the calculation of the several elasticities more apparent.

2. 4. 1. Final demand elasticities of CO_2 emissions

In this subsection, there will be derived the elasticity of the CO_2 emissions produced by the country's economy (c_{emis}) with respect to one component of total final demand (Y_i), whose formal definition is given by:

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[14] Indeed, the Kyoto Protocol, as well as other international agreements, focuses on activity solely in the national boundary. This is so because, among other factors, as the Protocol is legally binding, no government can be held responsible for the actions that occur in another country.

[15] Elasticity is the proportional (or percentage) change in one variable relative to the proportional change in another variable. In this particular case, it measures the percentage responsiveness of the level of CO_2 emissions to a 1 per cent change in another variable. In order to calculate a particular elasticity, there is the need to know the partial derivative of one variable (in this case the level of CO_2 emissions) with respect to the other, as well as the values of the variable at the point at which the elasticity is required.

$$\varepsilon_{Y_i}^{c_{emis}} = \frac{\partial c_{emis} / c_{emis}}{\partial Y_i / Y_i} \Leftrightarrow \varepsilon_{Y_i}^{c_{emis}} = \frac{\partial c_{emis} / \partial Y_i}{c_{emis} / Y_i} \quad (9).$$

To calculate the partial derivative of the CO_2 emissions produced by the country's economy (c_{emis}) with respect to one component of total final demand (Y_i), we have to differentiate equation (7) with respect to Yi. Therefore, equation (9) becomes:

$$\varepsilon_{Y_i}^{c_{emis}} = \frac{\partial c_{emis} / \partial Y_i}{c_{emis} / Y_i} = \frac{\left[\mathbf{e'C(I-A)}^{-1} + \mathbf{e'PH}\right] \frac{\partial \mathbf{y}}{\partial Y_i}}{c_{emis} / Y_i} = \frac{\left[\mathbf{e'C(I-A)}^{-1} + \mathbf{e'PH}\right]_i Y_i}{c_{emis}} \quad (10),$$

where $[\mathbf{e'C(I\text{-}A)}^{-1}+\mathbf{e'PH}]_i$ is the ith element of the vector $[\mathbf{e'C(I\text{-}A)}^{-1}+\mathbf{e'PH}]$.

2. 4. 2. Fuel use elasticities of CO_2 emissions

2. 4. 2. 1. Production fuel use elasticities of CO_2 emissions

By similar reasoning to that used to derive the elasticity previously presented, one can obtain other elasticities, such as, e.g., the elasticity of the CO_2 emissions produced by the country's economy (c_{emis}) with respect to the production fuel use coefficients (c_{fi}) as:

$$\varepsilon_{c_{fi}}^{c_{emis}} = \frac{\partial c_{emis} / \partial c_{fi}}{c_{emis} / c_{fi}} = \frac{\mathbf{e'} \frac{\partial \mathbf{C}}{\partial c_{fi}} \mathbf{(I-A)}^{-1} \mathbf{y}}{c_{emis} / c_{fi}} = \frac{e_f \left[\mathbf{(I-A)}^{-1} \mathbf{y}\right]_i c_{fi}}{c_{emis}} = \frac{e_f X_i c_{fi}}{c_{emis}} \quad (11),$$

where f is, as usual, the type of primary fuel under consideration (i.e.: f = coal, oil, natural gas).

2. 4. 2. 2. Final demand fuel use elasticities of CO_2 emissions

The elasticity of the CO_2 emissions produced by the country's economy (c_{emis}) with respect to the final demand fuel use coefficients (p_{fi}) is given by:

$$\varepsilon_{p_{fi}}^{c_{emis}} = \frac{\partial c_{emis} / \partial p_{fi}}{cc_{emis} / p_{fi}} = \frac{\mathbf{e'} \frac{\partial \mathbf{P}}{\partial p_{fi}} \mathbf{Hy}}{c_{emis} / p_{fi}} = \frac{e_f \left[\mathbf{Hy}\right]_i p_{fi}}{c_{emis}} \quad (12).$$

Of course, there are only three non-zero elasticities, one for each of the primary fuels directly used by final consumers.

2. 4. 3. Intermediate trading elasticities of CO_2 emissions

2. 4. 3. 1. The technical coefficients elasticity of CO_2 emissions

The elasticity of the CO_2 emissions produced by the country's economy (c_{emis}) with respect to the technical coefficients (a_{ij}) is given by:

$$\varepsilon_{a_{ij}}^{c_{emis}} = \frac{\partial c_{emis} / \partial a_{ij}}{c_{emis} / a_{ij}} = \frac{\mathbf{e'C}\frac{\partial\left[(\mathbf{I}-\mathbf{A})^{-1}\right]}{\partial a_{ij}}\mathbf{y}}{c_{emis} / a_{ij}} \qquad (13).$$

To differentiate $(\mathbf{I}\text{-}\mathbf{A})^{-1}$ with respect to a_{ij} $\left(\text{i.e.} \frac{\partial\left[(\mathbf{I}-\mathbf{A})^{-1}\right]}{\partial a_{ij}}\right)$ we write:

$$(\mathbf{I}\text{-}\mathbf{A})^{-1}[(\mathbf{I}\text{-}\mathbf{A})^{-1}]^{-1} = \mathbf{I} \Leftrightarrow (\mathbf{I}\text{-}\mathbf{A})^{-1}(\mathbf{I}\text{-}\mathbf{A}) = \mathbf{I} \qquad (14).$$

Differentiating both sides of (14) with respect to a_{ij} gives:

$$\frac{\partial\left[(\mathbf{I}-\mathbf{A})^{-1}(\mathbf{I}-\mathbf{A})\right]}{\partial a_{ij}} = 0 \Leftrightarrow \frac{\partial\left[(\mathbf{I}-\mathbf{A})^{-1}\right]}{\partial a_{ij}}(\mathbf{I}-\mathbf{A}) + (\mathbf{I}-\mathbf{A})^{-1}\frac{\partial(\mathbf{I}-\mathbf{A})}{\partial a_{ij}} = 0 \Leftrightarrow$$
$$\frac{\partial\left[(\mathbf{I}-\mathbf{A})^{-1}\right]}{\partial a_{ij}}(\mathbf{I}-\mathbf{A}) = -(\mathbf{I}-\mathbf{A})^{-1}\frac{\partial(\mathbf{I}-\mathbf{A})}{\partial a_{ij}} \qquad (15).$$

Now, if we post-multiply both sides of (15) by $(\mathbf{I}\text{-}\mathbf{A})^{-1}$ we get:

$$\frac{\partial\left[(\mathbf{I}-\mathbf{A})^{-1}\right]}{\partial a_{ij}}\mathbf{I} = -(\mathbf{I}-\mathbf{A})^{-1}\frac{\partial(\mathbf{I}-\mathbf{A})}{\partial a_{ij}}(\mathbf{I}-\mathbf{A})^{-1} \qquad (16).$$

So now we need to differentiate $(\mathbf{I}\text{-}\mathbf{A})$ with respect to a_{ij}. One can write:

$$\frac{\partial(\mathbf{I}-\mathbf{A})}{\partial a_{ij}} = -\mathbf{F}^{\mathbf{ij}} \qquad (17),$$

where we define the matrix $\mathbf{F}^{\mathbf{ij}}$ as:

$$\mathbf{F}_{rs}^{\mathbf{ij}} = \begin{Bmatrix} 1, \ r = i, s = j \\ 0, \text{otherwise} \end{Bmatrix} \qquad (18).$$

Therefore, substituting (17) into (16) we obtain:

$$\frac{\partial\left[(\mathbf{I}-\mathbf{A})^{-1}\right]}{\partial a_{ij}} = -(\mathbf{I}-\mathbf{A})^{-1}\left(-\mathbf{F}^{\mathbf{ij}}\right)(\mathbf{I}-\mathbf{A})^{-1} = (\mathbf{I}-\mathbf{A})^{-1}\mathbf{F}^{\mathbf{ij}}(\mathbf{I}-\mathbf{A})^{-1} \qquad (19).$$

Thus, substituting (19) into (13), the elasticity of CO_2 emissions with respect to the technical coefficients (a_{ij}) will be given by:

$$\varepsilon_{a_{ij}}^{c_{emis}} = \frac{\mathbf{e'C}\left[(\mathbf{I}-\mathbf{A})^{-1}\mathbf{F}^{\mathbf{ij}}(\mathbf{I}-\mathbf{A})^{-1}\right]\mathbf{y}}{c_{emis} / a_{ij}} \qquad (20).$$

Since the effect of the matrix $\mathbf{F}^{\mathbf{ij}}$ is to pick out the required elements of the other matrices (this matrix has a single element, the one which we are differentiating), (20) becomes:

$$\varepsilon_{a_{ij}}^{c_{emis}} = \frac{\left[\mathbf{e'C}(\mathbf{I}-\mathbf{A})^{-1}\right]_i \left[(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}\right]_j a_{ij}}{c_{emis}} = \frac{\left[\mathbf{e'C}(\mathbf{I}-\mathbf{A})^{-1}\right]_i X_j \, a_{ij}}{c_{emis}} \qquad (21).$$

As the input-output table which will be used is a (38x38) industry-by-industry table, this means that we can calculate 38x38=1444 elasticities of the CO_2 emissions (c_{emis}) with respect to the technical coefficients (a_{ij}). Of course, this means that it is problematic to deal with such an amount of data, particularly for policy purposes. Therefore, in order to 'condense' such information, as suggested by Proops et al. (1993: 145), there will be employed technology elasticities related to one sector at a time, namely calculating the elasticities corresponding to the technology of inputs to a sector, as well as the ones corresponding to the technology of outputs from a sector.

2. 4. 3. 2. The technology of inputs to a sector's elasticity of CO_2 emissions

The relationship of the technology of inputs to a sector may be summarised as the column sum of the technical coefficients, i.e.:

$$a_{.j} = \sum_{i=1}^{n} a_{ij} \qquad (22).$$

Accordingly, the elasticity of the CO_2 emissions produced by the country's economy (c_{emis}) with respect to the column sum of the technical coefficients ($a_{.j}$) may be expressed as the weighted sum of the single coefficient elasticities, $\varepsilon_{a_{ij}}^{c_{emis}}$, i.e., it is given by:

$$\varepsilon_{a_{.j}}^{c_{emis}} = \frac{\partial c_{emis} / \partial a_{.j}}{c_{emis} / a_{.j}} = \frac{1}{\sum_{i=1}^{n} \frac{a_{ij}}{a_{.j}} \frac{1}{\varepsilon_{a_{ij}}^{c_{emis}}}} = \sum_{i=1}^{n} \varepsilon_{a_{ij}}^{c_{emis}} \qquad (23).$$

2. 4. 3. 3. The technology of outputs from a sector's elasticity of CO_2 emissions

Similarly, the relationship of the technology of outputs from a sector may be summarised as the row sum of the technical coefficients, i.e.:

$$a_{i.} = \sum_{j=1}^{n} a_{ij} \qquad (24).$$

Hence, the elasticity of the CO_2 emissions produced by the country's economy (c_{emis}) with respect to the row sum of the technical coefficients ($a_{i.}$) may also be expressed as the weighted sum of the single coefficient elasticities, $\varepsilon_{a_{ij}}^{c_{emis}}$, i.e., it is given by:

$$\varepsilon_{a_{i.}}^{c_{emis}} = \frac{\partial c_{emis} / \partial a_{i.}}{c_{emis} / a_{i.}} = \frac{1}{\sum_{j=1}^{n} \frac{a_{ij}}{a_{i.}} \frac{1}{\varepsilon_{a_{ij}}^{c_{emis}}}} = \sum_{j=1}^{n} \varepsilon_{a_{ij}}^{c_{emis}} \qquad (25).$$

3. CO_2 emissions by the Portuguese economy

In this section, there will be presented an input-output empirical application of the energy-economy-environment interactions for Portugal, especially concerning the energy intensities and CO_2 emissions derived from fossil fuels use, according to the modelling approach described above.

3. 1. Data preparation[16]

3. 1. 1. Portuguese national accounts and the input-output table

A number of adjustments needs to be made to the way figures are presented by the Portuguese system of economic accounts, published by the National Institute of Statistics (INE, 1999), to achieve a valuation of the supply and use flows as consistently and homogenously as possible, and obtain the input-output tables that are the basis for the empirical analysis to be performed in this work. However, the estimation of such tables was only possible for 1992[17], because the 'auxiliary' data to perform the required treatments is only surveyed with a breakdown of all interindustry transactions (by industries and by products) and of final uses by product for the 1992 Portuguese national accounts.

It is also important to mention that in order to be able to explore alternative scenarios for electricity generation (see Cruz, 2002b), the electricity sector was disaggregated into three 'sub-sectors'[18]: 6A - Fossil Fuel Electricity Generation, 6B - Hydroelectricity, and 6C - Electricity Distribution. To perform this disaggregation, following Gay and Proops (1993), and Proops et al. (1993), it is assumed that:

- the two generating sectors (6A and 6B) sell all of their output to the distribution sector (6C)[19];
- the fuel inputs to electricity are attributed entirely to fossil fuel generation[20], and all other inputs are split between the two generating sectors in proportion to their total output; and
- all purchases of electricity by the remaining sectors and by final demand are supplied by electricity distribution.

This resulted in the use of a (38x38) industry-by-industry input-output table, for Portugal, in 1992. From this table was derived the matrix **A**, by dividing inter-industry flows by the total inputs (=total outputs) by industry at basic prices, as usual. It was also from this table that was derived matrix **H**, as well as the final demand vector **y**.

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16 A detailed description of the adjustments made to the Portuguese national accounts, as well as the characteristics and the adjustments made in the Portuguese energy data used may be found in Cruz (2002c).

17 Of course, the absence of more up-to-date data may constitute a restriction to providing useful information for practical policy decisions. However, the basic economic structure of the economy changes relatively slowly over time and therefore, for many aspects, the table(s) will be relevant over a reasonable period of time (Miller and Blair, 1985: 269). Nevertheless, the performance of the analysis for more recent years and the investigation of the reasons behind the changes which might have occurred (through structural decomposition analysis), should be explored as soon as the information becomes available, particularly concerning National Accounts.

18 This was done because of the need to distinguish fossil-fuel electricity generation from other electricity generation, since electricity obtained, e.g., from hydro, wind, and solar sources, do not correspond to CO_2 emissions.

19 This means that the two electricity-generating sectors have zero final demand.

20 Which means that hydroelectricity generation and the distribution side of electricity are recorded as using no fossil fuel at all, which is clearly an underestimate (Gay and Proops, 1993: 123).

3. 1. 2. The physical quantities of primary fossil fuels used in the Portuguese economy

To perform the study there is also the need to consider the (physical) quantities of primary fossil fuels used by each industry per unit of total output, as well as the quantities of fossil fuels used per unit of final demand. However, such data was generally not directly available in the appropriate, or consistent, form. Therefore, there was the need to make some assumptions and estimations in order to correlate the different data sources, namely the input-output tables (provided by the INE) and the energy balance statistics (supplied by the Portuguese Directorate General of Energy – DGE).

According to the 'Energy Balance' statistics for 1992 (DGE, 1995), the Portuguese economy total consumption of coal and (crude) oil was of 2,949,576 and 13,148,058 tonnes of oil equivalent (toe), respectively. These values were considered as credible totals of domestic energy use (by type of fuel) and it was from these that were derived the physical quantities of coal and oil used by each of the 38 sectors and by final consumers in 1992[21]. Then, dividing these values by the corresponding element of the total input (=total output) vector or by the final demand vector, it was possible to determine the primary energy intensities (or requirements) per unit of total output by sector (the 2x38 matrix **C**) and per unit of final demand (the 2x38 matrix **P**).

3. 1. 3. The carbon content of primary fuels

CO_2 emissions are produced when carbon-based fuels are burned. Therefore, after adjusting primary energy figures, it is possible to estimate CO_2 emissions from fuel combustion, by considering the carbon contents of each type of fuel. For this purpose, conversion factors from primary energy to CO_2 were applied. These conversion factors were calculated following the IPCC's default methodology to make countries' greenhouse gas emissions inventories (IPCC, 1996), and were arranged in a vector of CO_2 emission per unit (toe) of fuel burnt (the 2-vector **e**). Accordingly, it is assumed that each toe of coal burnt generates 3.88 tonnes of CO_2, and that each toe of oil burnt generates 3.04 tonnes of CO_2. These figures clearly show that the amounts of CO_2 emitted directly depend on the fuel, with more CO_2 being emitted per unit of energy content for coal than for oil (and for natural gas[22]).

3. 2. The input-output assessment of CO_2 emissions

In this section there will first be determined the CO_2 intensities per unit of total output and per unit of final demand, in terms of tonnes of CO_2 per million Portuguese Escudos (PTE).

[21] It is important to note that the use of natural gas was introduced in Portugal only in 1997. Thus, as the analysis done in this study is for 1992, only two primary energy sources were considered. Consequently, matrices **C** and **P** are of dimension (2x38), and vector **e** is a 2-vector.

[22] Likewise, it was also estimated that each toe of natural gas combusted generates 2.34 tonnes of CO_2. This result is not used here, as in 1992 there was no use of natural gas in Portugal.

Subsequently, there will be reported the total CO_2 emissions for a given structure of final consumption, both in aggregate and disaggregated to 38 sectors.

3. 2. 1. The CO_2 intensities

As derived from equation (8), the elements of the row-vector (**e'C**) represent the tonnes of CO_2 emitted directly by each sector, per million PTE of final demand for the output of that sector; and the elements of [**e'C**(**A**+**A**^{2}+…)] represent tonnes of CO_2 emitted throughout the rest of the economy (i.e. indirectly) by each sector, per million PTE of final demand for the output of that sector. Moreover, the elements of the vector (**e'P**), containing only two non-zero elements (one for each type of fuel), represent tonnes of CO_2 emitted per million PTE of demand by consumers for fuels. Thus, the sum of CO_2 intensities corresponding to total production demand and to direct consumption demand, represents tonnes of CO_2 emitted per million PTE of final demand, for each sector. Table 1 contains the estimated corresponding figures.

Concerning total CO_2 intensities, the energy sectors (except Hydroelectricity) are unsurprisingly the ones that appear in the upper ranking, followed also predictably by the Land Transport sector. The total CO_2 intensity of the two top sectors (Mining and Manufacture of Coal By-Products and Extraction of Crude Petroleum and Natural Gas; and Manufactured Refined Petroleum Products) is dominated (in 91.3 and 94.3 per cent, respectively) by the intensities corresponding to direct consumption demand. For all the other sectors, the CO_2 intensities correspond only to production demand (on the clear majority of them mainly to indirect production demand).

3. 2. 2. CO_2 emissions produced by the Portuguese economy

From equation (8), multiplying the CO_2 intensities presented above by the final demand vector, one achieves the corresponding tonnes of CO_2 emitted by each sector, which are shown also in Table 1.

In 1992, according to the estimation made through the model, 51,413.8 kilotonnes of CO_2 were emitted on Portuguese territory, derived from the use of fossil fuels, in order to satisfy the domestic and foreign final demand for goods and services domestically produced[23].

[23] This figure is slightly higher than the 45,165.9 kilotonnes of CO_2 reported by EEA (2002a), which were estimated also following the IPCC Guidelines (IPCC, 1996). It is important to remember that not only are some components of the data used in this work of poor quality, which implied the making of some assumptions, but also that only one coefficient was used for each fuel, which may have had some effect in this discrepancy.

Table 1
CO_2 intensities
and
CO_2 emissions produced by the Portuguese economy

unit for CO_2 intensities: tonnes of CO_2 / million PTE
unit for CO_2 emissions: 10^3 tonnes of CO_2

	CO_2 intensities (corresponding to:)						**CO_2 emissions produced by the Portuguese economy** (attributable to:)									
	Direct Production Demand +	Indirect Production Demand =	Total Production Demand +	Direct Consumption Demand =	Final Demand		Direct Production Demand	+	Indirect Production Demand	=	Total Production Demand +	Direct Consumption Demand	=	Final Demand		
	e'C	**e'C $(A+A^2+...)$**	**e'C $(I-A)^{-1}$**	**e'P**	**Total CO_2 Intensity**	*Total CO_2 Intens. Rank.*	**e'Cy**	(6)/(10)	**e'C $(A+A^2+...)$y**	(7)/(10)	**e'C $(I-A)^{-1}$y**	**e'PZy**	(9)/(10)	**Total CO_2 emissions**	*Total CO_2 Emis. Rank.*	*% Distrib of CO_2 Emis. by Ind.*
	(1)	(2) = (3)-(1)	(3)	(4)	(5) = (3)+(4)		(6)	%	(7) = (8)-(6)	%	(8)	(9)	%	(10) = (8)+(9)		
01 Agriculture, Hunting and Related Service Activities	1.12	1.89	3.01	0.00	3.01	17	394.0	37.1	668.2	62.9	1 062.2	0.0	0.0	1 062.2	12	2.1
02 Forestry, Logging and Related Service Activities	0.71	0.36	1.07	0.00	1.07	28	17.5	66.5	8.8	33.5	26.3	0.0	0.0	26.3	36	0.1
03 Fishing and Related Service Activities	3.20	0.97	4.17	0.00	4.17	13	191.1	76.7	58.0	23.3	249.0	0.0	0.0	249.0	26	0.5
04 Mining and Manufacture of Coal By-Products	34.99	2.94	37.93	397.56	435.49	1	13.6	30.6	1.1	2.6	14.8	29.8	66.8	44.6	33	0.1
05 Extr. Crude Petrol. ..., & Man. Refined Petroleum Prod.	7.67	1.87	9.54	158.85	168.39	2	844.7	9.9	205.7	2.4	1 050.3	7 448.3	87.6	8 498.7	1	16.5
6A Fossil Fuel Electricity Generation	73.74	1.00	74.75	0.00	74.75	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	37	0.0
6B Hydroelectricity	0.00	0.17	0.17	0.00	0.17	38	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	37	0.0
6C Electricity Distribution	0.00	33.83	33.83	0.00	33.83	4	0.0	0.0	5 735.5	100.0	5 735.5	0.0	0.0	5 735.5	2	11.2
07 Gas Production and Distribution	14.06	9.58	23.64	0.00	23.64	6	142.1	59.5	96.8	40.5	238.9	0.0	0.0	238.9	27	0.5
08 Water Supply	0.00	6.01	6.01	0.00	6.01	11	0.0	0.0	161.8	100.0	161.8	0.0	0.0	161.8	29	0.3
09 Extr. & Man. of Ferrous & Non-Ferrous Ores & Metals	5.24	6.31	11.55	0.00	11.55	7	327.9	0.0	394.7	0.0	722.6	0.0	0.0	722.6	19	1.4
10 Extraction and Manuf. of Non-Metallic Minerals	6.09	4.71	10.80	0.00	10.80	8	865.2	56.4	668.3	43.6	1 533.5	0.0	0.0	1 533.5	10	3.0
11 Manuf. of Chemicals and Chemical Products	5.98	2.55	8.53	0.00	8.53	9	1 515.8	70.1	646.4	29.9	2 162.2	0.0	0.0	2 162.2	8	4.2
12 Manufacture of Fabricated Metal Products	0.19	2.99	3.18	0.00	3.18	16	43.4	6.0	682.0	94.0	725.4	0.0	0.0	725.4	18	1.4
13 Man. of Electrical and Non-Electrical Machinery & Equipm.	0.06	1.26	1.32	0.00	1.32	25	35.6	4.9	694.1	95.1	729.7	0.0	0.0	729.7	17	1.4
14 Manufacture of Transport Equipment	0.15	1.11	1.26	0.00	1.26	27	57.9	11.7	437.4	88.3	495.3	0.0	0.0	495.3	21	1.0
15 Manufacture of Food Products and Beverages	0.36	1.97	2.34	0.00	2.34	22	431.8	15.6	2 336.6	84.4	2 768.4	0.0	0.0	2 768.4	7	5.4
16 Manufacture of Tobacco and Tobacco Products	0.19	0.29	0.48	0.00	0.48	37	27.9	39.2	43.3	60.8	71.2	0.0	0.0	71.2	32	0.1
17 Manufacture of Textiles and Clothing	0.37	2.40	2.78	0.00	2.78	19	388.7	13.5	2 495.1	86.5	2 883.8	0.0	0.0	2 883.8	6	5.6
18 Manufacture of Leather and Footwear	0.20	1.10	1.30	0.00	1.30	26	66.2	15.3	367.3	84.7	433.5	0.0	0.0	433.5	24	0.8
19 Other Manuf. Products (incl. Wood, Cork & Furniture)	0.68	1.97	2.65	0.00	2.65	21	202.9	25.7	587.7	74.3	790.6	0.0	0.0	790.6	16	1.5
20 Man. of Pulp, Paper, Paper Prod. & Printing Products	1.18	3.09	4.27	0.00	4.27	12	225.4	27.7	587.7	72.3	813.1	0.0	0.0	813.1	15	1.6
21 Manufacture of Rubber and Plastic Products	0.18	2.80	2.98	0.00	2.98	18	11.3	6.0	177.9	94.0	189.2	0.0	0.0	189.2	28	0.4
22 Construction	0.67	2.76	3.42	0.00	3.42	14	995.1	19.5	4 103.3	80.5	5 098.4	0.0	0.0	5 098.4	3	9.9
23 Recycling, Recovery and Repair services	0.20	0.34	0.53	0.00	0.53	36	48.5	36.6	84.0	63.4	132.6	0.0	0.0	132.6	31	0.3
24 Wholesale and Retail Trade	0.16	1.93	2.09	0.00	2.09	23	269.0	7.5	3 325.8	92.5	3 594.8	0.0	0.0	3 594.8	5	7.0
25 Hotel and Restaurant Services	0.12	2.56	2.67	0.00	2.67	20	86.8	4.4	1 902.3	95.6	1 989.0	0.0	0.0	1 989.0	9	3.9
26 Land Transport and Transport Via Pipeline Serv.	21.24	2.50	23.74	0.00	23.74	5	4 545.2	89.5	535.3	10.5	5 080.5	0.0	0.0	5 080.5	4	9.9
27 Water and Air Transport Services	4.91	1.52	6.43	0.00	6.43	10	726.5	76.4	224.5	23.6	951.0	0.0	0.0	951.0	14	1.8
28 Supporting and Auxiliary Transport Services	0.17	3.11	3.27	0.00	3.27	15	17.4	5.1	324.7	94.9	342.1	0.0	0.0	342.1	25	0.7
29 Post and Telecommunication Services	0.03	1.01	1.04	0.00	1.04	30	4.4	3.2	132.5	96.8	136.9	0.0	0.0	136.9	30	0.3
30 Financial Intermediation Services (except Insurance and ...)	0.00	0.56	0.56	0.00	0.56	35	0.1	0.2	37.8	99.8	37.8	0.0	0.0	37.8	35	0.1
31 Insurance and Pension Funding Services	0.06	1.54	1.59	0.00	1.59	24	1.4	3.5	38.8	96.5	40.2	0.0	0.0	40.2	34	0.1
32 Real Estate Services and Other Renting Services	0.01	0.99	1.00	0.00	1.00	31	14.3	1.5	954.4	98.5	968.7	0.0	0.0	968.7	13	1.9
33 Education and R & D Services	0.02	0.55	0.57	0.00	0.57	34	17.3	3.6	463.9	96.4	481.2	0.0	0.0	481.2	22	0.9
34 Health and Veterinary Market Services	0.01	0.82	0.83	0.00	0.83	33	7.6	1.6	464.5	98.4	472.1	0.0	0.0	472.1	23	0.9
35 Other Services (Market and Non-Market)	0.07	0.91	0.98	0.00	0.98	32	39.6	6.8	542.3	93.2	581.9	0.0	0.0	581.9	20	1.1
36 Public Administration Non-Market Services	0.09	0.97	1.06	0.00	1.06	29	100.7	8.6	1 070.4	91.4	1 171.1	0.0	0.0	1 171.1	11	2.3
							12 676.8	**24.7**	**31 258.9**	**60.8**	**43 935.7**	**7 478.1**	**14.5**	**51 413.8**		100

The top five sectors 'responsible' for those CO_2 emissions are Extraction of Crude Petroleum, and Manufacture of Refined Petroleum Products (16.5 per cent), Electricity Distribution (11.2 per cent), Construction (9.9 per cent), Land Transport and Transport Via Pipeline Services (9.9 per cent), and Wholesale and Retail Trade (7 per cent). This means that the former four sectors account for almost half of total CO_2 emissions attributable to production in the Portuguese economy. Moreover, as the CO_2 emissions by the Extraction of Crude Petroleum, and Manufacture of Refined Petroleum Products sector are mainly associated with the use of private cars, and as the production of CO_2 emissions by the Land Transport and Transport Via Pipeline Services is mainly connected with freight and passengers transport, one can say that (personal and public) transport (of passengers and goods) was 'responsible' for almost one-quarter of all the emissions that occurred in Portugal in 1992.

Relating these results with those concerning CO_2 intensities, one can notice that the sectors that are more highly CO_2 intensive are not necessarily the ones whose production generates more CO_2 emissions. This is explained by what might be called the 'scale effect' of the final demand (corresponding to the fact that the total CO_2 emissions of any sector are given by the product of the intensity per unit of final demand and the level of final demand).

Another key result is the significant importance of the indirect production demand for fuels in the production of CO_2 emissions. Indeed, more than half (60.8 per cent) of the CO_2 emissions are attributable to indirect demand, while 24.7 per cent of the emissions are attributable to direct demand for fossil fuels by industries; the remaining 14.5 per cent are directly attributable to household demand for fossil fuels.

3. 3. The elasticities of total CO_2 emissions produced by the Portuguese economy

In this section, there will be offered an examination of the impacts of changes in specific parameters at the level of Portuguese energy-related CO_2 emissions. This will be done by analysing the elasticities of total CO_2 emissions produced by the Portuguese economy with respect to (some of) the parameters. The figures are presented in Table 2, corresponding to situations of *ceteris paribus*, and were obtained according to the details given in Section 2.4.

Column (1) presents the elasticities of the CO_2 emissions produced by the Portuguese economy with respect to each component of total final demand. For example, the value of 0.17 for the elasticity of CO_2 emissions with respect to the final demand for the Extraction of Crude Petroleum and Natural Gas, and Manufacture of Refined Petroleum Products sector, indicates that if the final demand for this sector increases (decreases) by 1 per cent, then total CO_2 emissions in the Portuguese economy will increase (diminish) by 0.17 per cent. Additionally, one can say that the final demand for this sector's output is the one to which the Portuguese CO_2 emissions are most sensitive, followed by the final demand for the outputs of the following sectors: Electricity

Table 2
Elasticity of total CO_2 emissions produced by the Portuguese economy (c_{emis})
with respect to the...

unit: % change

	Final demand		Production fossil fuel use coefficients				Final demand fossil fuel use coefficients		Column sum of the technological coefficients		Row sum of the technological coefficients	
	$\varepsilon_{Y_i}^{c_{emis}}$		$\varepsilon_{c_{coal,i}}^{c_{emis}}$		$\varepsilon_{c_{oil,i}}^{c_{emis}}$		$\varepsilon_{p_{coal,i}}^{c_{emis}}$	$\varepsilon_{p_{oil,i}}^{c_{emis}}$	$\varepsilon_{a_{.j}}^{c_{emis}}$		$\varepsilon_{a_{i.}}^{c_{emis}}$	
	(1)	*ranking*	(2)	*ranking*	(3)	*ranking*	(4)	(5)	(6)	*ranking*	(7)	*ranking*
01 Agriculture, Hunting and Related Service Activities	0.02	12	0.00		0.02	8	0.00	0.00	0.03	9	0.03	7
02 Forestry, Logging and Related Service Activities	0.00	36	0.00		0.00	20	0.00	0.00	0.00	36	0.00	30
03 Fishing and Related Service Activities	0.00	26	0.00		0.01	14	0.00	0.00	0.00	34	0.00	27
04 Mining and Manufacture of Coal By-Products	0.00	33	0.01	4	0.00	33	0.00	0.00	0.00	37	0.01	21
05 Extr. Crude Petrol. ..., & Man. Refined Petroleum Prod.	0.17	1	0.00		0.04	4	0.00	0.14	0.01	21	0.03	8
6A Fossil Fuel Electricity Generation	0.00	37	0.17	1	0.18	1	0.00	0.00	0.00	30	0.35	1
6B Hydroelectricity	0.00	37	0.00		0.00	36	0.00	0.00	0.00	38	0.00	36
6C Electricity Distribution	0.11	2	0.00		0.00	36	0.00	0.00	0.35	1	0.24	2
07 Gas Production and Distribution	0.00	27	0.00		0.01	15	0.00	0.00	0.00	31	0.00	25
08 Water Supply	0.00	29	0.00		0.00	36	0.00	0.00	0.01	27	0.00	23
09 Extr. & Man. of Ferrous & Non-Ferrous Ores & Metals	0.01	19	0.01	3	0.00	16	0.00	0.00	0.02	15	0.02	11
10 Extraction and Manuf. of Non-Metallic Minerals	0.03	10	0.04	2	0.02	5	0.00	0.00	0.05	6	0.07	4
11 Manuf. of Chemicals and Chemical Products	0.04	8	0.00	5	0.07	3	0.00	0.00	0.03	10	0.07	5
12 Manufacture of Fabricated Metal Products	0.01	18	0.00		0.00	22	0.00	0.00	0.02	12	0.01	16
13 Man. of Electrical and Non-Electrical Machinery & Equipm.	0.01	17	0.00		0.00	26	0.00	0.00	0.02	18	0.00	26
14 Manufacture of Transport Equipment	0.01	21	0.00		0.00	23	0.00	0.00	0.01	20	0.00	31
15 Manufacture of Food Products and Beverages	0.05	7	0.00	8	0.01	9	0.00	0.00	0.07	4	0.03	9
16 Manufacture of Tobacco and Tobacco Products	0.00	32	0.00		0.00	27	0.00	0.00	0.00	35	0.00	38
17 Manufacture of Textiles and Clothing	0.06	6	0.00		0.01	11	0.00	0.00	0.07	5	0.02	12
18 Manufacture of Leather and Footwear	0.01	24	0.00		0.00	21	0.00	0.00	0.01	25	0.00	32
19 Other Manuf. Products (incl. Wood, Cork & Furniture)	0.02	16	0.00	6	0.01	13	0.00	0.00	0.02	16	0.01	17
20 Man. of Pulp, Paper, Paper Prod. & Printing Products	0.02	15	0.00		0.01	10	0.00	0.00	0.03	11	0.02	10
21 Manufacture of Rubber and Plastic Products	0.00	28	0.00		0.00	29	0.00	0.00	0.01	26	0.00	22
22 Construction	0.10	3	0.00		0.02	6	0.00	0.00	0.09	3	0.01	14
23 Recycling, Recovery and Repair services	0.00	31	0.00		0.00	19	0.00	0.00	0.00	32	0.00	29
24 Wholesale and Retail Trade	0.07	5	0.00		0.01	12	0.00	0.00	0.10	2	0.04	6
25 Hotel and Restaurant Services	0.04	9	0.00		0.00	18	0.00	0.00	0.04	7	0.01	20
26 Land Transport and Transport Via Pipeline Serv.	0.10	4	0.00	7	0.17	2	0.00	0.00	0.02	14	0.10	3
27 Water and Air Transport Services	0.02	14	0.00		0.02	7	0.00	0.00	0.01	28	0.01	18
28 Supporting and Auxiliary Transport Services	0.01	25	0.00		0.00	24	0.00	0.00	0.02	17	0.01	15
29 Post and Telecommunication Services	0.00	30	0.00		0.00	31	0.00	0.00	0.01	29	0.00	24
30 Financial Intermediation Services (except Insurance and ...)	0.00	35	0.00		0.00	35	0.00	0.00	0.01	24	0.01	19
31 Insurance and Pension Funding Services	0.00	34	0.00		0.00	34	0.00	0.00	0.00	33	0.00	34
32 Real Estate Services and Other Renting Services	0.02	13	0.00		0.00	28	0.00	0.00	0.03	8	0.02	13
33 Education and R & D Services	0.01	22	0.00		0.00	30	0.00	0.00	0.01	23	0.00	37
34 Health and Veterinary Market Services	0.01	23	0.00		0.00	32	0.00	0.00	0.01	22	0.00	35
35 Other Services (Market and Non-Market)	0.01	20	0.00		0.00	25	0.00	0.00	0.01	19	0.00	28
36 Public Administration Non-Market Services	0.02	11	0.00		0.00	17	0.00	0.00	0.02	13	0.00	33
	1.00		0.22	+	0.63	+	0.00	+ 0.14				
								1.00				

Distribution (0.11), Construction (0.10), Land Transport and Transport Via Pipeline Services (0.10), and Wholesale and Retail Trade (0.07)[24].

Moreover, as results from the definition of these elasticities (see equation 10), their sum is equal to one, which means that if the final demand of all the sectors in the economy increase (decrease) by 1 per cent, then total CO_2 emissions will enlarge (decline) in 1 per cent.

In columns (2) and (3) are shown the elasticities of the CO_2 emissions produced by the Portuguese economy with respect to production fuel use coefficients.

Concerning coal, by far the largest elasticity is the one corresponding to its use by the Fossil Fuel Electricity Generation sector. Indeed, the 0.17 figure is more than four times bigger than the next largest value, which is 0.04 for the Extraction and Manufacture of Non-Metallic Minerals sector. It is also noticeable that the great majority of the values in column (2) are zero, as there is no direct use of coal in the production of the corresponding sectors.

Regarding the use of oil, the largest elasticity is also for Fossil Fuel Electricity Generation (0.18), followed by Land Transport and Transport Via Pipeline Services (0.17), Manufacture of Chemicals and Chemical Products (0.07), Extraction of Crude Petroleum and Natural Gas, and Manufacture of Refined Petroleum Products (0.04), and Extraction and Manufacture of Non-Metallic Minerals (0.02).

From the analysis of the figures in columns (2) and (3), it can also be said that if all the sectors raise (reduce) the direct use of coal in their production by 1 per cent, the overall augment (reduction) in CO_2 emissions would be of 0.22 per cent, while the same percent change in the direct use of oil by all the sectors would imply a change of 0.63 per cent in CO_2 emissions.

In the fourth and fifth columns, there are only two non-zero values. This is logical, as they represent the elasticities of the CO_2 emissions produced by the Portuguese economy with respect to the final demand fuel use coefficients (for coal and oil, respectively). Thus, the value of 0.001 in column (4) means that by changing the final demand for coal by 1 per cent, the overall CO_2 emissions will vary by 0.001 per cent; and the value of 0.14 in column (5) signifies that if the final demand for oil increases (decreases) by 1 per cent, the total CO_2 emissions will increase (decrease) by 0.14 per cent. Therefore, one can say that the CO_2 emissions are much more sensitive to the final demand for oil than to the final demand for coal.

Therefore, the results of the elasticities of total CO_2 emissions with respect to the production (columns (2) and (3)) and to the final demand (columns (4) and (5)) fuel use coefficients, suggest that any policy to fight against CO_2 emissions by directly interfering with industries or households direct consumption of fuels, has better chances of reaching more significant effects in CO_2

[24] As there are 38 sectors, one would expect that all of these values would be considerably less than unity.

emissions by marginally 'acting' on oil than on coal use[25], as the reader would have already thought (whether based on the results presented on the previous sections, or only on the basis of a sensible perception of the way the Portuguese economy performs).

The sixth column contains the elasticities of the CO_2 emissions produced by the Portuguese economy with respect to the column sum of the technical coefficients ($a_{.j}$). For example, the value of 0.35 for the Electricity Distribution sector means that if this sector raises (reduces) the use of all its inputs by 1 per cent, then the CO_2 emissions will increase (decline) by 0.35 per cent. Thus, it is possible to say that, following the Electricity Distribution sector, the sectors whose contribution can be bigger to reduce CO_2 emissions in Portugal, by becoming more efficient in their use of inputs are: Wholesale and Retail Trade; Construction; Manufacture of Food Products and Beverages; and Manufacture of Textiles and Clothing.

Column (7) shows the elasticities of the CO_2 emissions produced by the Portuguese economy with respect to the row sum of the technical coefficients ($a_{i.}$). As an example, the result of 0.35 in Fossil Fuel Electricity Generation means that if the use of the sector's output as an input to all the sectors increases (decreases) by 1 per cent, the overall CO_2 emissions will increase (decrease) by 0.35 per cent. Moreover, the other products whose more efficient use (as inputs) by all the sectors may lead to more significant reductions in CO_2 emissions are those from the following sectors: Electricity Distribution; Land Transport and Transport Via Pipeline Services; Extraction and Manufacture of Non-Metallic Minerals; and Manufacture of Chemicals and Chemical Products. This clearly indicates that the greatest reduction in CO_2 emissions is to be achieved if all the sectors become more efficient in the use of first electricity, and then transport.

4. Final comments

The results obtained in this empirical application are clear evidence of the 'value-added' that the input-output technique may bring to policy analysis, as an approach which takes economic interrelations into account when analysing CO_2 production (Gay and Proops, 1993: 123).

Indeed, it appears that there is significant general awareness about the CO_2 emissions that occur from direct energy use in households and private cars, as well as about the CO_2 emitted directly in energy industries and by the transport sectors. But more significant is that it appears that there does not exist a general awareness about the major importance of industries' indirect

[25] Moreover, as results from the definition of these elasticities (and obviously, first of all, from the fact that the total use of fuels in the economy is 'divided' in fuel use for production demand and fuel use for final demand, and the CO_2 emissions here estimated are only the ones that result from coal and oil combustion), the sum of the totals of columns (2), (3), (4) and (5) is equal to one. This means that if all the sectors raise (reduce) the direct use of coal and oil in their production by 1 per cent, and simultaneously the final demand for coal and oil increase (decrease) also by 1 per cent, then total CO_2 emissions will enlarge (decline) in 1 per cent.

production demand for fuels, and consequently of the fact that the great majority of direct consumption is 'responsible' for much more CO_2 production indirectly than directly.

Therefore, the analysis performed here may help policy-makers in dealing with the problem of CO_2 emissions as they are better informed about the root causes of some outcomes.

It may also help to make final consumers aware that the non-primary energy goods and services they purchase from industry sectors have entailed CO_2 emissions in their production. Indeed, through adequate sensitisation campaigns it is possible to show to final consumers that they have much more 'responsibility' for CO_2 emissions than they usually assume. Then, it is possible to pass the 'message' to them that their individual action in terms of the goods and services they purchase (or not) may 'count' in the global struggle against climate change.

Concerning the sensitivity analysis of the CO_2 emissions produced by the Portuguese economy, is possible to say that two major kinds of conclusion can be made from it.

On the one hand, as the data we use is not perfectly known, this analysis can provide a guide to which components of the data set need to be determined most accurately. Actually, e.g., if the elasticity of total CO_2 emissions with respect to a specific item of data is large, the inaccuracy in such a particular item of data matters much more than if the elasticity is small.

On the other hand, such an analysis has a role to play in policy analysis and formulation. Indeed, it was here shown that its use allows, e.g., the identification of the potential for reducing CO_2 emissions through changes in the technologies used (through the analysis of the elasticities associated with the elements of the technological matrices **A**, **C** and **P**), as well as the examination of the changes in the structure of the final demand which would be most worthwhile for reducing CO_2 emissions (through the analysis of the elasticities associated with the specific elements of the final demand vector **y**). This is a particularly valuable feature, because as interest is in identifying policies that may reduce CO_2 emissions, one may consider how changing these parameters may be effective in achieving this aim.

Thus, it is possible to claim that one of the key accomplishments of the use of this type of modelling, which integrates economic, energy and environmental interactions in an input-output framework, is that it allows the analysis of how energy, and therefore CO_2 emissions, are related to industrial production, and ultimately to final demand, making it a tool particularly important for (*ex ante*[26] and/or *ex post*) policy analysis purposes.

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[26] Indeed, both the model and the database are formulated in terms of detailed technical parameters, on a multisectoral basis, that can be directly evaluated by technical experts and readily changed in order to explore the consequences of alternative scenarios (see Cruz, 2002b and 2002c).

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