A Structural Decomposition Analysis of Primary Energy Use in Portugal

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Abstract

The Portuguese energy sector changed dramatically in the last two decades, with the adoption of natural gas and an exponential increase in the penetration rate of wind power. During the same period, the Portuguese economy continued its transition into a service economy that started in the 1980's. The combination of these two phenomena led to a modest decline of the primary energy intensity of the Portuguese economy. The goal of this paper is to identify the main driving factors of changes in primary energy use (PEU) over the period 1995-2010. To do so, we perform a Structural Decomposition Analysis, using the D&L technique. Our model allows to determine the relative contributions of the economic and energy transitions in the country. Two main factors of change with opposite effects were found: the final demand of non-energy products contributed to significantly increase PEU while sectoral energy intensity reduced the level of PEU. Moreover the drastic changes in the energy sector had a positive effect on PEU, though relatively small compared to structural changes in the productive sectors and improvements of sectoral energy intensity. The results give insights on the most suitable areas for intervention to boost energy decoupling in the Portuguese economy and also provide lessons to other economies pursuing a radical transition in their energy sectors.

KEYWORDS: Structural decomposition analysis; primary energy supply; Portugal; energy transition

1 Introduction

The European Union (EU) is currently committed to increase the share of energy consumption produced from renewable resources to 20% by the year 2020 (EU, 2009; Brown, 2013; Haas et al., 2011; Amorim et al., 2010). In this respect, Portugal has achieved an outstanding progress, passing from a renewable share of 19% in 1995 to 35% in 2010, while at the same time primary energy use increased by 31% from 896.76 to 1175.44 $[PJ]$ (DGEG, 2012). Because of this fact, Portugal has become a role model for many developed countries, including the two major economies, see e.g. Rosenthal (2010) and Heer and Langniß (2007).

Particularly, the electricity sector had the largest transition. In 1995 electricity was generated mainly from fossil fuels (40% coal and 31% oil) and hydropower. However, by 2010, renewables reached 11 $[GW]$ of installed capacity and 54% of total electricity generation while coal and oil accounted for only 18% of total generation (DGEG, 2014a,b; IEA, 2011)..

The introduction of natural gas imports from Algeria in 1997 was also fundamental for the energy transition in the country. By 2010, natural gas generation accounted for 28% of total electricity generation with an installed capacity of 4.9 $[GW]$ (DGEG, 2014a,b; IEA, 2011). In addition, natural gas for final consumption reached 16% of total energy use of the industrial sector and 10% of the residential and service sectors (DGEG, 2012). Even though natural gas use is still relatively low in comparison to other European countries (Amador, 2010), it has helped diversify the primary energy mix and reduce the growth rate of CO_2 emissions (Arto et al., 2009; Robaina Alves and Moutinho, 2013; Diakoulaki and Mandaraka, 2007).

Nevertheless, the energy performance of the country has been poor (Henriques, 2011). Total primary energy use did not experience a significant reduction with respect to economic output during the studied period. Technological improvements were limited, e.g. the evolution of technical efficiency of energy use slowed down since around 1990 (Serrenho et al., 2014b), and were offset by growing energy needs of private transportation and comfort in the service sector (Henriques, 2011; Serrenho et al., 2014a). Moreover, high and volatile energy prices, mainly of crude oil and gas (EIA, 2014; EUROSTAT, 2014b; IEA, 2012), represented a threat to growth prospects but also an incentive for renewable energy development (Amador, 2010).

During the same period, Portugal also experienced significant economic transitions: The country continued the structural shift from manufacturing into services, which started since the 1980's (Henriques, 2011; EUROSTAT, 2014a; BdP, 2009). Moreover, the integration to the European Economic and Monetary Union promoted further transformation of the productive structure and bounded the economy into a single EU currency (Aguiar-Confraria et al., 2012; BdP, 2009; Leite, 2010). Finally, in the late 2000's the country suffered the financial crisis of 2007-2009 (Farto and Morais, 2011; French et al., 2009; Gros, 2012; Lourtie, 2012) and needed to enter a macroeconomic adjustment process (Claessens et al., 2010; Costa, 2012; Rodrigues and Reis, 2012)

The fact that the impressive development of the energy sector between 1995 and 2010 did not derived in better energy performance might be also related to economic transitions. However there is little understanding of the relative contributions of energy and economic transitions to the overall energy performance, which is fundamental for defining measures to improve the current status.

The goal of the present paper is to identify the main drivers of change in total primary demand in Portugal during the period of 1995-2010 using decomposition analysis.

Decomposition analysis is a procedure that helps identify the underlying factors behind changes in aggregate indicators of the economy (e.g. energy, environmental, socio-economic indicators) (Hoekstra and van den Bergh, 2003; Miller and Blair, 2009; Rose and Casler, 1996). It is used to evaluate the effectiveness of policy measures and determine future policy interventions (Hoekstra and van den Bergh, 2002; Liu and Ang, 2007).

Structural Decomposition Analysis (SDA) is the specific decomposition methodology for input-output analysis. The advantage of SDA over other decomposition methodologies is that it provides more detailed results for the whole economy, which correspond to the relative complexity of its required data (Su and Ang, 2012). In addition, SDA has been applied to energy consumption indicators since the 1980's (Hoekstra and van den Bergh, 2002) and it is now widely recognized tool for policy analysis (Su and Ang, 2012).

The analysis carried out in the present study complements the existing literature in two different ways:

On the one hand, it is the first SDA of primary energy transition in Portugal. Existing decomposition studies with other methodologies that included Portugal 1995-2007 found that the structural effect (i.e. changes in the productions structure of the economy) mostly contributed to increase the Portuguese final energy intensity while the intensity effect (i.e. technological changes) mostly contributed to reduce it (Henriques, 2011; Voigt et al., 2014; Mendiluce et al., 2010). However in comparison to other major economies, Portugal has had a lower energy intensity level due to differences in productive structure (Henriques, 2011; Alcántara and Duarte, 2004)

On the other hand, the proposed decomposition model is innovative because it allows to separate the effect of structural changes in the energy sector from structural changes in non-energy sectors in contrast to conventional models. Our model combines characteristics of the *hybrid-unit model* (Bullard and Herendeen, 1975; Miller and Blair, 2009) and the *direct impact coefficient model* (Rose and Casler, 1996).

The paper proceeds as follows. Section 2 reviews the theory of SDA and identifies the innovations introduced in the present study. Section 3 reviews the source data and the processing algorithms. Section 4 presents and discusses the results and Section 5 presents final remarks.

2 Theory

This Section describes the methodological framework of our proposed decomposition model. It begins by introducing the different components of the model: the national economy in Section 2.1, the energy sector in Section 2.2 and link between both in Section 2.3. Section 2.4 presents the complete decomposition model. Finally, in Section 2.5, the general form of the SDA used in this study is described. In addition, the description of source data and data manipulation is reported in Section 3.

2.1 National economy

According to the System of National Accounts (UN, 2009) goods and services (e.g., diesel or coal) are classified into a set of n_P commodities or products. There is consumption by a set of n_S industries (e.g., pulp and paper) and by n_F categories of final demand (households, government, fixed capital formation and exports). These products are in turn produced domestically or imported, and industries purchase primary inputs such as labor and capital. Such a clear demarcation between products and industries is usually referred to as a make-use or supply use (SUT) framework (EUROSTAT, 2014a; Rodrigues and Rueda-Cantuche, 2013; Suh, 2009)

Within this framework, the economic components of the decomposition model is understood as a set of coefficients whose product connects the total final demand in the economy to the total economic output in each industry:

$$\mathbf{x}^M = \mathbf{L}^M \mathbf{C}^M \mathbf{s}^M \tag{1}$$

where

- Vector $\mathbf{s}^M$ of length n_F is the *economic scale* factor, i.e. the total demand (in monetary terms) of each final demand category.

- Matrix $\mathbf{C}^M$ of size $n_P \times n_F$ accounts for the *economic composition* effect. Each element C_{ij}^M expresses (in adimensional terms) the amount of product i which is consumed by each unit of total final demand j.

- Finally, matrix $\mathbf{L}^M$ of size $n_S \times n_P$ describes the *economic technology*. Each element L_{ij} expresses (in adimensional terms) the total output of industry i which is required to generate one unit of product demand j.

Note: In the previous and following expressions italic denotes a scalar, lowercase bold denotes a vector and uppercase bold a matrix. Vectors are in column format and $'$ denotes transpose.

2.2 Energy sector

The energy sector model is based on Portuguese energy balances (obtained from the Directorate-General for Energy and Geology DGEG, 2012). Energy balances data are arranged to conform to SUT framework, which consists of a set of n_T energy technologies (such as oil refineries or wind) that both receive and deliver elements from a set of n_C energy carriers (such as crude oil or electricity).

Energy carriers are classified as 1) Final energy carriers - which are energy products, e.g. electricity and fueloil, for direct use of the economic sectors, and 2) Primary energy carriers - n_P endogenous and imported raw energy sources for conversion into final energy carriers, e.g. crude oil and renewables.

Within this framework, energy carriers are used either by energy technologies for energy conversion processes or by the set of n_R non-energy sectors while only final energy carriers are delivered from energy technologies. It is worth to notice that the sets of non-energy sectors of the rest of the economy in the energy model differ from the set of sectors in the economic model since the classifications are obtained from different sources.

Finally, the energy component of our model accounts from the transformation between total primary energy and the final energy use by the rest of the economy:

$$\mathbf{p} = \mathbf{L}^E \mathbf{C}^E \mathbf{s}^E. \tag{2}$$

where

- Vector $\mathbf{s}^E$ of length n_R is the *final energy demand* factor, i.e. the total demand (in energy units) of non-energy sectors of the rest of the economy.

- Matrix $\mathbf{C}^E$ of size $n_C \times n_R$ describes the *energy composition*. Element C^E_{ij} expresses the fraction of the energy demand of sector j which is provided by energy carrier i.
- Matrix $\mathbf{L}^E$ of size $n_P \times n_C$ describes the *energy technology*. Element L^E_{ij} expresses the primary energy consumption of source i which is required to generate a unit of final energy of carrier j.

2.3 Link between models

Linking the national economy and energy models is done by including the concept of energy intensity, i.e. the energy use required by a specific sector to produce a unit of output.

$$\mathbf{E}^S = \left[\frac{s^E_i}{x^M_j}\right]$$

where

- Matrix $\mathbf{E}^S$ of size $n_R \times n_S$, the *final energy intensity* matrix. Element E^S_{ij} expresses the final energy of type i (in energy units) which is required to generate one unit of output of industry j (in monetary units).

2.4 The energy-economic decomposition model

The addition of final energy intensity matrix closes the model and establishes a link between the economic (Eq. 1) and the energy components (Eq. 2) as:

$$\mathbf{p} = \mathbf{L}^E\mathbf{C}^E\mathbf{E}^S\mathbf{L}^M\mathbf{C}^M\mathbf{s}^M. \tag{3}$$

The energy-economic model combines characteristics of two conventional models: The *hybrid-unit model* (Bullard and Herendeen, 1975; Miller and Blair, 2009) and the *direct impact coefficient model* of final energy use (or *intensity factor model*) (Rose and Casler, 1996; Wachsmann et al., 2009). In contrast to conventional models, the proposed formulation is able to distinguish the effect of structural change in the energy sector (through $\mathbf{L}^E$) from structural change of non-energy sectors (through $\mathbf{L}^M$).

There are three additional points –scope, residential energy use and double-counting– that merit consideration:

Scope: The present study is concerned with the accounting of the primary energy required to generate the final energy demand that occurs in Portugal. Hence, the primary energy associated with the final energy consumed within Portugal to generate exports is taken into account. However, the primary energy associated with final energy consumed abroad to generate Portuguese imports is not. That exercise would require constructing a multi-regional model, with an explicit description of international supply chains.

Residential energy use: As in the *direct impact coefficient model*, the residential sector should be dealt with separately from productive sectors. In this work, we limit our analysis to primary energy use by productive sectors since, through them, we are able to understand the relative contribution of the energy and economic transitions on primary energy use.

Double-counting: In hybrid models it is important to avoid double-counting, i.e., to make sure that the same flow is not being considered twice, first in economic and then in physical units (Strømman et al., 2009). This point must be taken into consideration here because the energy sector is represented in monetary terms as part of the national economic. Hence, to avoid double-counting it is important that in the final energy intensity matrix the columns which correspond to the economic representation of energy sector be set to zero.

2.5 Structural decomposition analysis

Given an endogenous variable which is defined as the product of n exogenous variables, SDA is a technique which decomposes the total variation in the endogenous variable as a sum of variations of the exogenous variables (Rose and Casler, 1996; Hoekstra and van den Bergh, 2002, 2003).

From the proposed model (Eq. 3) in a given year, the SDA explains the variation in total primary energy between two years t_1 and t_2, $\Delta\mathbf{p} = \mathbf{p}(t_2) - \mathbf{p}(t_1)$, as:

$$\Delta\mathbf{p} = \delta\mathbf{L}^E + \delta\mathbf{C}^E + \delta\mathbf{E}^S + \delta\mathbf{L}^M + \delta\mathbf{C}^M + \delta\mathbf{s}^M. \tag{4}$$

where each term $\delta\mathbf{X}$ is the contribution of factor $\mathbf{X}$ to the observed variation in total primary energy consumption.

There are different mathematical techniques to determine the values of the elements in Eq. 4. In this work we use the D&L technique (Dietzenbacher and Los, 1998) that calculates the effect of each factor as the average of all equivalent decomposition forms. The D&L technique was selected because it offers a complete decomposition (no residual term), passes the time reversal test and is zero-value and negative-value robust. Also, it gives a range and distribution (i.e. standard deviation) of factor effects.

Dietzenbacher and Los (1998) show that the number of all decomposition forms is equal to n!, where n is the number of factors . In our case, n=6, and hence there are 6!=720 equivalent decomposition forms. These many forms make the formulation cumbersome and computer intensive. However, an important computational development of the D&L approach was the combinatorial approximation provided by Seibel (2003), based on previous work by De Haan (2001), which simplifies the formulation and reduces computer-intensity.

3 Materials and methods

This Section reports the source data and the data processing required to perform the SDA. Section 3.1 describes the economic data and Section 3.2 describes the energy data.

3.1 Economic data

The main data source for the economic model were the EUROSTAT Portuguese SUTS for the period 1995-2010 (EUROSTAT, 2014a).

In accordance with the SNA (UN, 2009, 1999), the EUROSTAT use data is reported in purchaser prices whereas the supply data in reported in basic prices with additional columns of trade and transport margins and taxes less subsidies on products. Within this framework, the economic model was constructed using the augmented Leontief formulation (Rodrigues and Rueda-Cantuche, 2013; Wachsmann et al., 2009; Weidema et al., 2009), with an explicit sector of trade and transport margins. That is, the system was structured as:

$$\mathbf{x} = \mathbf{Zi} + \mathbf{Yi};$$
$$\mathbf{x}' = \mathbf{i}'\mathbf{Z} + \mathbf{i}'\mathbf{V},$$

where $\mathbf{x}$ is augmented total output, $\mathbf{Z}$ are augmented intermediate transactions, $\mathbf{y}$ is augmented final demand, $\mathbf{x}$ are augmented primary inputs, $\mathbf{i}$ is a vector of ones and $'$ is tranpose.

Each of these components is in turn:

$$\mathbf{Z} = \begin{bmatrix} \mathbf{O} & \mathbf{U} & \mathbf{m} \\ \mathbf{M} & \mathbf{O} & \mathbf{o} \\ \mathbf{t}' & \mathbf{o}' & 0 \end{bmatrix}; \quad \mathbf{v} = \begin{bmatrix} \mathbf{im}' & \mathbf{o}' & 0 \\ \mathbf{tax}' & \mathbf{o}' & 0 \\ \mathbf{o}' & \mathbf{va}' & 0 \end{bmatrix}; \mathbf{Y} = \begin{bmatrix} \mathbf{F} \\ \mathbf{O} \\ \mathbf{o}' \end{bmatrix}; \quad \mathbf{x} = \begin{bmatrix} \mathbf{q} \\ \mathbf{g} \\ m \end{bmatrix},$$

where $\mathbf{M}$, $\mathbf{U}$ and $\mathbf{F}$ are the make, intermediate and final use matrices; $\mathbf{im}$, $\mathbf{tax}$ and $\mathbf{va}$ are the imports, product taxes and value added vectors; $\mathbf{q}$ and $\mathbf{g}$ are commodity and economic activity total output; $\mathbf{t}$ and $\mathbf{m}$ are the components of trade and transport margins in nonmargin products and the provision of trade and transport margins by margin products; finally $\mathbf{O}$ and $\mathbf{o}$ are a matrix and a vector of zeros.

The monetary scale factor is:

$$\mathbf{s}^M = \mathbf{i}'\mathbf{F}.$$

The monetary composition factor is:

$$\mathbf{C}^M = \mathbf{F}\,\mathrm{diag}(\mathbf{s})^{-1}.$$

The monetary technology factor $\mathbf{L}^M$ is the submatrix defined by rows $[n_P + 1 : n_P + n_S]$ and columns $[1 : n_P]$ of $\mathbf{L}$ defined as:

$$\mathbf{L} = \left(\mathbf{I} - \mathbf{Z}\,\mathrm{diag}(\mathbf{x})^{-1}\right)^{-1}.$$

The economic technology matrix thus obtained is equivalent to having used the product-by-product industry technology assumption (Miller and Blair, 2009; Ten Raa and Rueda-Cantuche, 2003).

The tables for the period 1995-2006 followed the CPA2002 classification for commodities and the NACE1.1 classification for economic activities with $n_S = n_P = 59$ elements, whereas the tables for the period 2006-2010 follwed the CPA2008 classification for commodities and the NACE2 classification for economic activities, with $n_S = n_P = 65$ elements. The classifications of the two time periods were aggregated to a consistent classification of $n_S = n_P = 49$ elements based on EUROSTAT (2008) and EUROSTAT (2009).

The aggregation was performed with the use of bridge matrices, $\mathbf{G}$, of size $n_1 \times n_2$ whose entries are non-negative and whose column sums equal one. Such an object ensures that $\mathbf{x}_2 = \mathbf{G}\mathbf{x}_1$ is an aggregation of n_1 elements of the the original vector $\mathbf{G}$ of n_2 elements. Matrix $\mathbf{G}$ is a left-aggregation matrix, and its transpose it the right aggregation matrix.

The only problematic aspect of the classification conversion was *C33: Repair and installation of machinery and equipment*, which in the CPA2008 and NACE2 classifications exists as a distinct sector while in the CPA2002 and NACE1.1 classifications is reported as component of nine different types of machinery. We approached this problem by allocating maintenance to each of the machinery sectors in the 2006-2010 data, in proportion to that machinery sectors' share of total output. That is, if we are aggregating the commodity classification, then $\mathbf{G}$ is:

$$\begin{aligned}\mathbf{G} &= \operatorname{diag}(\mathbf{x}^T)\mathbf{G}^T \operatorname{diag}(\mathbf{q}^T)^{-1};\\ \mathbf{q}^T &= (\mathbf{G}^T)'\mathbf{x}^T;\\ \mathbf{x}^T &= \mathbf{G}^T \operatorname{diag}(\mathbf{x}^M)\mathbf{q},\end{aligned}$$

where $G^T_{ij} = 1$ if element i in the new classification is aggregation of element j in the old classification and $G^T_{ij} = 0$ otherwise and $\operatorname{diag}(x)^M$ is a vector of ones except that $x^M_i = 0$ if element i is maintenance. The activity classification aggregation would be identical except that the weight vector would be $\mathbf{g}$ rather than $\mathbf{q}$.

A sensitivity analysis was performed by examining a set of scenarios where all maintenance is allocated to each single machinery sector. Each of these scenarios was constructed by making $\mathbf{G} = \mathbf{G}^T$ with the exception that if j is maintenance now $G^T_{ij} = 0$ if i is not the specified machinery sector.

Finally, to perform the SDA it was necessary to convert the data from current to constant prices (Dietzenbacher and Temurshoev, 2012; Miller and Blair, 2009). Because the EUROSTAT source data are reported both in current, *cp*, and in previous year prices, *pyp* a time series in constant prices of 2002 was obtained by deflating/inflating the entire dataset with the appropriate chain indices (Dietzenbacher and Hoen, 1998; Jackson and Murray, 2004). Some entries reported a zero value in the *pyp* tables while the *cp* value was different from zero. When such a situation occurred, the deflator used was the average deflator -across industries- for that commodity class (similar to the double deflation method UN, 1993; Miller and Blair, 2009).

3.2 Energy data

Energy balances for the period 1995-2010 were obtained from the Directorate-General for Energy and Geology (DGEG, 2012). These balances consist of $n_R = 24$ sectors of final energy demand, $n_T = 34$ energy technologies, and $n_C = 39$ energy carriers, of which $n_{CF} = 14$ are final energy carriers and $n_{CP} = 19$ are primary energy carriers.

The final energy intensity matrix was obtained as:

$$\mathbf{E}^S = \text{diag}(\mathbf{s}^E)\mathbf{G}^R \,\text{diag}(\mathbf{g}^{RS})^{-1}\mathbf{G}^S;$$
$$\mathbf{g}^{RS} = \mathbf{G}^S\mathbf{x}^M,$$

where $\mathbf{G}^R$ has size $n_R \times n_J$ and $\mathbf{G}^S$ has size $n_J \times n_S$, there is at most one non-zero entry (of value one) per row of $\mathbf{G}^R$ and at most one non-empty entry (of value one) per column of $\mathbf{G}^S$. The columns of $\mathbf{G}^S$ which correspond to the monetary representation of the energy sector must have only zeros.

Yearly energy supply and use tables were built with 38 energy carriers and 34 energy technologies based on the national energy balances. The intermediate energy use table, $\mathbf{U}^E$, represents the amount of each specific energy carrier that is used as an input by an energy technology. The final energy use table, $\mathbf{F}^E$, represents the amount of each specific energy carrier that is used an input by a non-energy sector (including households and exports). Vector $\mathbf{vs}$ represents variations of stock. The energy make table, $\mathbf{M}^E$, represents the total supply of energy carriers of each energy technology. Vector $\mathbf{w}$ represents the energy transformation loss of each technology (it can take only nonpositive values). Matrices $\mathbf{p}^D$ and $\mathbf{p}^M$ are the vectors of domestic and imported final energy inputs. These different objects are organized as:

$$\mathbf{x}^E = \mathbf{Z}^E\mathbf{i} + \mathbf{Y}^E\mathbf{i};$$
$$(\mathbf{x}^E)' = \mathbf{i}'\mathbf{Z}^E + \mathbf{i}'\mathbf{V}^E.$$

Each of these components is in turn:

$$\mathbf{Z}^E = \begin{bmatrix} \mathbf{O} & \mathbf{U}^E \\ \mathbf{M}^E & \mathbf{O} \end{bmatrix}; \qquad \mathbf{V}^E = \begin{bmatrix} (\mathbf{p}^D)' & \mathbf{o}' \\ (\mathbf{p}^M)' & \mathbf{o}' \\ \mathbf{o}' & \mathbf{w}' \end{bmatrix};$$
$$\mathbf{Y}^E = \begin{bmatrix} \mathbf{F}^E & \mathbf{f}^H & \mathbf{vs} \\ \mathbf{O} & 0 & 0 \end{bmatrix}; \qquad \mathbf{x}^E = \begin{bmatrix} \mathbf{q}^E \\ \mathbf{g}^E \end{bmatrix},$$

The energy scale factor is:

$$\mathbf{s}^E = \mathbf{i}'\mathbf{F}^E.$$

The energy composition factor is:

$$\mathbf{C}^E = \mathbf{F}^E \operatorname{diag}(\mathbf{s}^E)^{-1}.$$

Notice that in the previous two expressions the rows of $\mathbf{F}^E$ corresponding to non-energy uses of energy carriers must be set to zero.

The energy technology factor $\mathbf{L}^E$ is given by:

$$\begin{aligned}
\mathbf{L}^E &= \mathbf{PL}[1:n_P, 1:n_P]; \\
\mathbf{P} &= \begin{bmatrix} \operatorname{diag}(\mathbf{p}^D) \\ \operatorname{diag}(\mathbf{p}^M) \end{bmatrix} \operatorname{diag}(\mathbf{t}) \operatorname{diag}(\mathbf{q})^{-1}; \\
\mathbf{L} &= \left(\mathbf{I} - \mathbf{Z}^E \operatorname{diag}(\mathbf{x}^E)^{-1}\right)^{-1},
\end{aligned}$$

where the matrix formed by vectors $\mathbf{p}^D$ and $\mathbf{p}^M$ corresponds to the bridge matrix $\mathbf{G}$ of the *hybrid-unit model* (Miller and Blair, 2009). Additionally, $\mathbf{t}$ is a vector that transforms the flows of renewable electricity and final energy imports into the equivalent non-renewable primary energy that would be needed if the same amount of electricity or energy imports had been produced by existing energy technology within the country (i.e. the partial substitution method for energy accounting, see IEA, 2014, UN, 1982 and Bhattacharyya, 2011). To determine the coefficients of $\mathbf{t}$ for a given year, the average conversion process of thermoelectric generation –in the case of imported and renewable electricity– and oil refineries –in the case of imported oil products– were considered (DGEG, 2012).

4 Results

This section presents the results of the SDA applied to primary energy use (PEU) by productive sectors in Portugal between 1995 and 2010. Moreover, an overview of total PEU and energy performance in Portugal is portrayed.

4.1 Total primary energy use

Portugal increased the use of primary energy from 896.76 $[PJ]$ in 1995 to 1175.44 $[PJ]$ in 2010 (31% growth). However, the upward trend peaked at 1229 $[PJ]$ in 2005 followed by a solid decline (Figure 1).

The Portuguese primary energy mix changed dramatically with the introduction of natural gas in 1997 and the increase of renewable energy production up to 35% share of total primary energy supply. Before 2005, the major

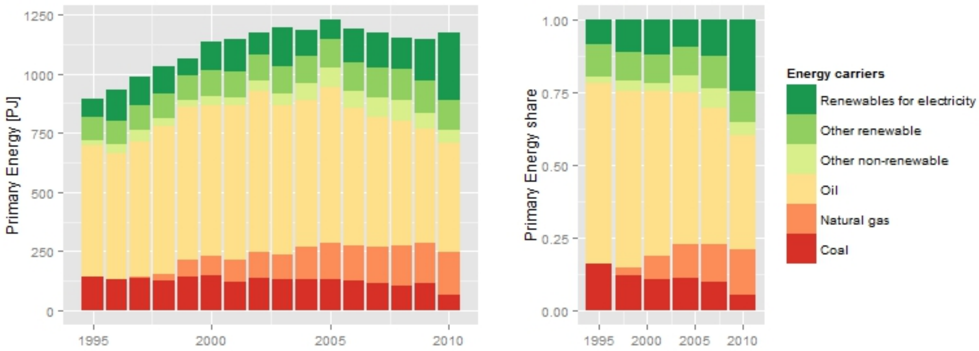

Figure 1: Total Primary Energy use

transition was based on the substitution of crude oil by natural gas since renewable production had volatile variations without a clear trend. However, after 2005, renewable energy production doubled, i.e. 203 to 415 $[PJ]$, in 5 years, which together with the decrease in total PEU and the slowing down of natural gas imports (19% vs. 79% increase in the previous lustrum) derived in a radically different primary energy mix.

Furthermore primary energy intensity had a small reduction (-14.8%, Figure 2) though the highest reduction was achieved after 2005. Between 1995 and 2005, the country was unable to reduce its energy requirements per unit of GDP but rather they were almost constant (avg. 7.97 $[MJ/Euro] \pm 5\%$).

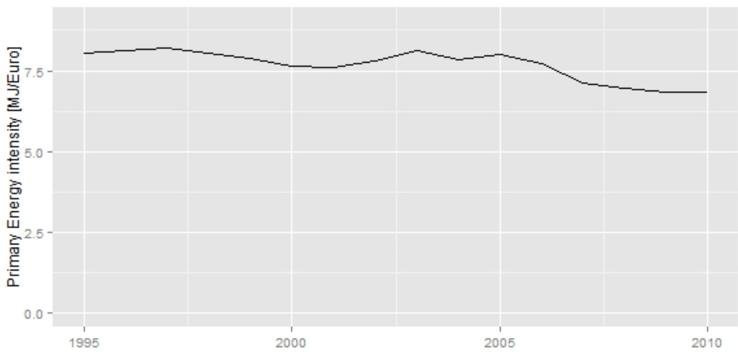

Figure 2: Overall primary energy intensity

Prices of crude oil and natural gas are related to the drastic changes after 2005. World crude oil prices had a sharp increase since 2001 (over 4 times higher in 2010 than in 2000) (EIA, 2014). Portugal coped with this by importing larger quantities of natural gas to substitute for crude oil for power generation before 2005. However, natural gas prices almost doubled between 2004 and 2010 with a large price shock in 2008 (EUROSTAT, 2014b; IEA, 2012). The latter fact led to a major focus on renewable energy production to reduce economic vulnerability caused by price increases of fossil energy carriers.

4.2 Productive structure and energy use

In the period 1995-2010, the Portuguese economy continued the transition into a service economy that started in the 1980's (Henriques, 2011; Serrenho et al., 2014b), i.e. a composition shift of output and energy use into the service sector. To illustrate the structural changes that the country underwent, Figure 3 depicts the distribution of the Portuguese GDP by sector.

In the figure, manufacturing industries are divided into energy and non-energy intensive as done by Weber (2009) based on their individual intensities. The energy intensive industry include pulp and paper, basic chemical and nonmetallic mineral industries while the non-energy intensive industry consists of the rest of the manufacturing industries. In addition, the primary sector corresponds to agriculture, fishing, forestry and related activities.

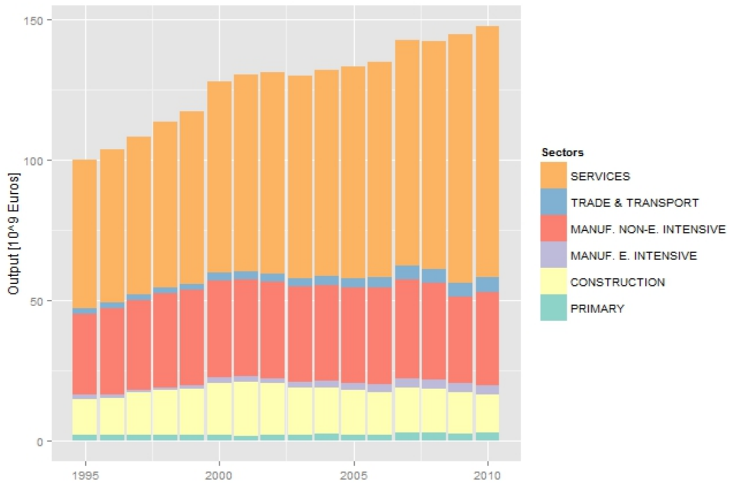

Figure 3: GDP by sector

The service sector in 1995 already had the largest share of GDP (53%) and continued growing to 60.5% by 2010, which confirms the servicification of the economy. The trade & transport sector almost doubled its output from 1.9 to 5.3 billion euros, which shows an increase of connectivity in the country. However, the share of transport & trade remained very small (max.

3.5%). Another sector that experienced significant increases in output was the energy intensity industries (1.5 to 3.2 billion euros) but as well as the trade & transport sector, its relative contribution was small (max. 2.2%). On the other hand, the non-energy intensive industry, construction sector and primary activities reduced their share in output, being the most significant reduction in non-energy intensive industries from 28.8% to 22.5% share.

The PEU associated to productive sectors increased from 553 to 699 $[PJ]$ between 1995 and 2010, though it peaked by 751 $[PJ]$ in 2005 (similar to total primary energy supply, see Figure 1). Additionally, after the latter year, the renewable energy share for productive sectors has been higher than for the whole economy, e.g. in 2010, productive sector-related primary renewable energy use had a 41% share while the whole economy had a 35% renewable share (i.e. including the residential sector).

Furthermore, the sectoral primary energy intensity, PEU by sector with respect to its output (Table 1), gives insights on the relative energy performance of each sector.

Table 1: Sectoral primary energy intensity in $[MJ/Euro]$

Sector	1995	1998	2001	2004	2007	2010
Primary	14.52	12.14	15.71	11.12	10.31	10.16
Construction	2.08	2.07	1.94	2.18	1.58	1.77
Energy intensive manufacturing	116.50	197.06	116.64	86.44	65.10	66.97
Non-energy intensive manufacturing	4.54	4.26	4.16	4.15	3.88	4.24
Trade & Transport	36.56	41.84	33.29	29.24	22.96	15.26
Services	2.08	2.47	2.54	2.75	2.43	2.35

The service sector performed poorly since it was the only sector that increased its primary energy intensity (13%), i.e. its energy use increased disproportionally to the growth of its output. This fact is explained by the increased comfort-related energy use, e.g. for heating and cooling, as pointed out by Henriques (2011). Conversely, trade & transport, energy intensive industries and primary sector had significant reduction in their primary energy intensities (-58%, -43% and -30%, respectively). Finally, the non-energy intensive industry slightly reduced their intensity (-6.4%, only better than the service sector).

Since the service sector and the non-energy industry account for the 80-83% share of GDP and about half (44% - 50%) of PEU by productive sectors, their poor energy performance diminished the effect of improvements by other industries on the overall energy performance of the country. For example, the slow evolution in technical exergy efficiency in the last two decades (Serrenho et al., 2014b).

4.3 Structural Decomposition Analysis

The overall results of the decomposition analysis are shown in Table 2. The SDA coefficients are presented for the total economy as well as for each category of final demand for non-energy products.

Table 2: SDA of primary energy use by productive sectors of categories of demand for non-energy products: Portugal 1995-2010

Final demand	$\Delta\mathbf{p}$	$\delta\mathbf{L}^E$	$\delta\mathbf{C}^E$	$\delta\mathbf{E}^S$	$\delta\mathbf{L}^M$	$\delta\mathbf{C}^M$	$\delta\mathbf{s}^M$
Total	145.98	-12.08	41.19	-212.60	-38.97	34.10	334.34
Residential	74.18	-6.27	19.54	-77.62	-2.41	3.41	137.54
Non-profit organizations	4.42	-0.10	0.89	-1.81	0.56	-0.34	5.21
Government	34.21	-1.14	6.83	-14.42	9.85	6.35	26.75
Exports	47.04	-0.21	6.54	-73.20	-50.98	39.71	125.18
Capital	-13.87	-4.36	7.40	-45.55	4.01	-15.03	39.66

There was increase of 145.98 $[PJ]$ of PEU by productive sectors over the studied period. Demand of non-energy products by residential consumers had the largest impact on PEU while government and export final demand also contributed to increase the level of energy use.

Changes in the final demand for non-energy products ($\delta\mathbf{s}^M$) had the largest effect on PEU growth. However this effect was offset, but not entirely, by improvements in sectoral energy intensity ($\delta\mathbf{E}^S$). The positive effect of ($\mathbf{E}^E$) was caused by 1) improvements in technical efficiency of final energy use (though limited according to Serrenho et al., 2014b), 2) price increases of non-energy product due to high prices of energy inputs, 3) and reductions in intensity of energy services (see Guevara et al., 2014).

The drastic changes brought by the transition of the energy sector ($\delta\mathbf{L}^E$) had a positive effect on PEU yet relatively small compared to structural changes, i.e. the transition into a service economy ($\delta\mathbf{L}^M$). However, compared to the positive effect of improvements of sectoral energy intensity, the effect of energy and economic transitions are considerably smaller. In the case of the energy sector, the latter fact suggests that, regardless the significant changes in the energy mix, primary-to-final energy conversion efficiencies might have had minor improvements.

Shifts in composition of final demand for energy and non-energy products ($\delta\mathbf{C}^E$ and $\delta\mathbf{C}^M$, respectively) contributed to increase PEU by similar amounts. This suggests that energy products with large related PEU increased their share, e.g. larger use of electricity in the service sector. On the other hand, export composition was the main driving force of $\delta\mathbf{C}^M$, which means that Portuguese non-energy exports consisted of increasing shares of products with large related PEU (see also Amador, 2012).

For a historical analysis, Figure 4 depicts the SDA results of the evolution of PEU by productive sectors.

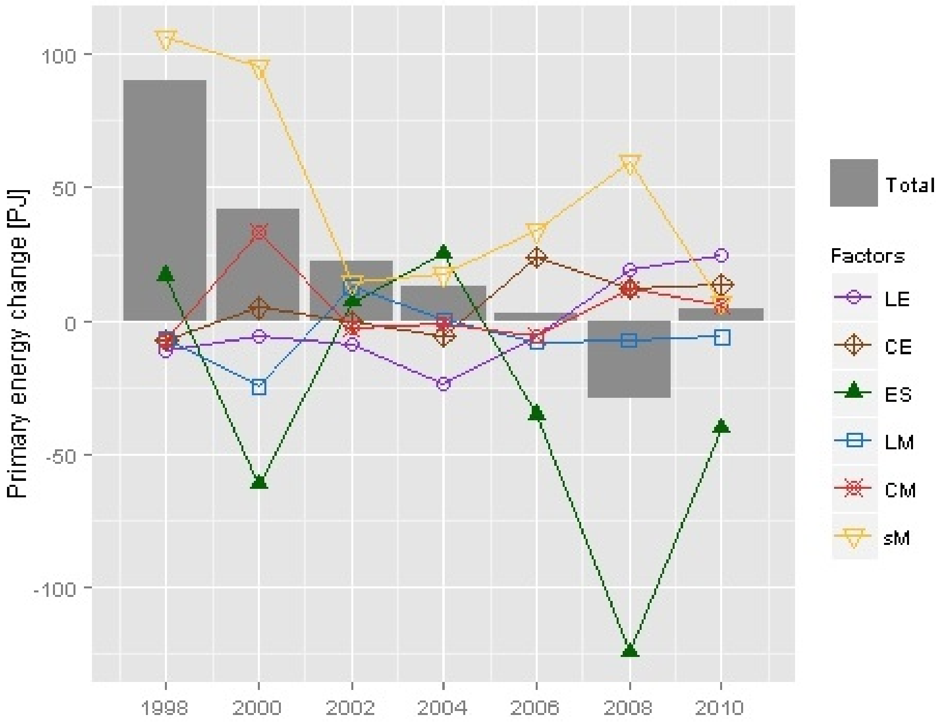

Figure 4: SDA of the evolution of primary energy use by productive sectors: Portugal 1995-2010.

The interval 1995-2000 was characterized by a sharp rise in PEU, mainly driven by final demand of non-energy products ($\delta\mathbf{s}^M$). This was caused by the prosperous economic performance of the country that boosted private consumption (due to real per capita income improvements) and eventually led to the EU integration of the country in 1999 (Aguiar-Confraria et al., 2012; BdP, 2009; Mata and N., 2003). Other factors had only relatively minor effects before 1998. However, in the interval 1998-2000, 1) composition of final demand of non-energy products ($\delta\mathbf{C}^M$) contributed to increase PEU due to a shift of demand towards non-energy products with larger related PEU (e.g. land transport); 2) structural changes ($\delta\mathbf{L}^M$) had a positive effect, which reflects economic transition brought by the EU integration; and 3) sectoral energy intensity ($\delta\mathbf{E}^S$) improved which is related to the expansion of natural gas for final consumption that allowed the use of more efficient technology by productive sectors.

After Portugal joined the EU, the economy performance became weak and suffered a contraction in 2003 (Aguiar-Confraria et al., 2012; BdP, 2009). The latter slowed down PEU growth between 2000 and 2004, mainly caused by a sharp decrease of $\delta\mathbf{s}^M$. During this interval changes in the energy sector ($\delta\mathbf{L}^E$) had a positive effect on PEU due to increasing imports of natural gas that helped improve primary-to-final conversion efficiencies for electricity generation, especially during 2002-2004. In addition, the case of the negative effect of $\delta\mathbf{E}^S$ reflects the loss in productivity and non-price competitiveness experienced in the country (see BdP, 2009; Farto and Morais, 2011).

In the interval 2004-2006, PEU remained almost constant. Even though changes in final demand for non-energy products ($\delta\mathbf{s}^M$) had a negative effect in PEU, as well as, the composition of demand for energy products. However, this was partially offset by advances in sectoral energy intensity. The decreasing effect of $\delta\mathbf{E}^S$ can be explained by the rise of oil and natural gas prices (EIA, 2014; EUROSTAT, 2014b), which forced productive sectors to rise prices , which reduces energy intensity, and pursue improvements in productivity and energy performance (though relatively small, see Table 1and Serrenho et al., 2014b).

The interval 2006-2008 was characterized by a significant reduction of PEU. The combination of the 2007 financial crisis, high and increasing energy prices (with a big oil and natural gas price shocks in 2008) and the launch of regulations on industrial energy efficiency (such as the SGCIE, see MEI, 2008) led the productive sectors to rise prices even further and keep pursuing progress in productivity and energy performance. In addition, some less efficient industries that could not cope with the crisis were forced to shut down, which lift the average energy efficiency of productive sectors. Shifts in composition of final demand for energy and non-energy products ($\delta\mathbf{C}^E$ and $\delta\mathbf{C}^M$, respectively) contributed to increase PEU due to shifts in final demand towards energy and non-energy products with larger associated PEU. Furthermore, $\delta\mathbf{s}^M$ had a large increasing effect on PEU, which implies an increase in final demand despite the financial crisis. This puzzling result might be explained by rising private consumption due to the sense of partial recovery from the economic recession of 2003, and increased government spending, which reinforced the image of economic recovery (BdP, 2009; Leite, 2010).

Changes in the energy sector had a negative effect between 2006 and 2010, which was caused by the deceleration of the rate of substitution of oil by natural gas for power generation and the shift towards primary renewable energy. The fact that increasing shares of renewable energy contributed to a rise in PEU is related to the method to account for primary equivalent energy from renewables (see Section 3.2), which strengthen the impact of the slow progress of conversion efficiency of conventional thermoelectric technologies. Additionally, structural changes had a modest but positive effect on PEU along 2004-2010, caused by the continuing transition into services.

Finally, in the interval 2008-2010, the country was severely hit by the international crisis and experienced a large contraction in 2009. Changes in final demand of non-energy products ($\delta \mathbf{s}^M$) had a small effect on PEU due to the reduction of private consumption and governmental austerity measures (Claessens et al., 2010; Costa, 2012). PEU slightly increased by the effect of $\delta \mathbf{L}^E$, $\delta \mathbf{C}^E$, $\delta \mathbf{C}^M$ and $\delta \mathbf{s}^M$ despite the counteracting effect of $\delta \mathbf{L}^M$ and $\delta \mathbf{E}^S$ (not as high as in the previous interval because of a drop in energy prices in 2009).

There is an additional point that merit consideration: the effect of energy sector transitions ($\delta \mathbf{L}^E$). The calculation of this effect depends on the approach to account for primary renewable energy used. In this work, we used the partial substitution method (see Section 3.2), which magnifies the primary renewable energy use and reinforces the impact of conventional thermoelectric primary-to-final conversion efficiencies. This fact causes that $\delta \mathbf{L}^E$ mainly represents the effect of improvements in thermoelectric conversion efficiencies in an equivalent all-non-renewable energy sector.

Table 3 shows the results of SDA primary energy use by productive sectors in Portugal 1995-2010, using the partial substitution method and the physical content method (IEA, 2014). The results show that the impact of using the physical content method do not considerably affect the effect of most factors except the $\delta \mathbf{L}^E$. The latter is caused by the assumption that primary-to-final conversion of renewables is 100% and hence any shift to renewable energy will improve the overall conversion efficiency of the economy.

The selection between the two methods depends on the aim of the study. On the one hand, the partial substitution method puts emphasis on the current structure of the energy sector. For this method, the share of renewables in primary energy use reflects the amount of fossil energy and related emissions that have been spared by the economy. On the other hand, the physical content method puts emphasis on a future ideal structure of the energy sector, i.e. an all renewable energy sector with 100% conversion efficiency. While the first method is more suitable for the analysis of mainstream technology

Table 3: SDA primary energy use by productive sectors: Portugal 1995-2010. Comparison between methods to account for primary equivalent energy of renewables

Method	$\Delta\mathbf{p}$	$\delta\mathbf{L}^E$	$\delta\mathbf{C}^E$	$\delta\mathbf{E}^S$	$\delta\mathbf{L}^M$	$\delta\mathbf{C}^M$	$\delta\mathbf{s}^M$
Partial substitution	145.98	-12.08	41.19	-212.6	-38.97	34.1	334.34
Physical content	51.05	-79.65	28.97	-200.98	-36.81	32.31	307.21

and how renewable energy helps reduce emissions and fossil carrier use, the latter method helps determine at what degree the energy sector is evolving.

5 Conclusions

In this paper, we performed a SDA of primary energy use in Portugal between 1995 and 2010 to identify its main driving factors. Particularly, we focused on understanding the relative contribution of the substantial energy and economic transitions that the country underwent in the last two decades.

We proposed a decomposition model that combines characteristics of the two conventional SDA models applied to energy studies. Our model enables the separation of the structure of energy sector from the rest of the economy and also allows the disaggregation of primary energy uses by sector, by non-energy products and by categories of final demand.

The SDA revealed the major driving factor of the increasing trend in primary energy use was the final demand of non-energy products, especially before 2000, when the country had had several years of thriving economic growth just before joining the European Union. However, this factor had less impact in the following years due to weak economic growth and the 2003 and 2009 recessions that hurt public and private consumption.

The composition of final demand of energy and non-energy products also contributed to increase the level of primary energy use. Households, government and foreign consumers demanded more and more products with large associated primary energy (e.g. glass and air transport), as well as, industries partially shifted to final energy carriers with lower primary-to-final conversion efficiencies such as electricity.

There were three counteracting factors that partially offset the effect of magnitude and composition of final demand. Though, despite the impressive development of the energy sector and the transition into a service economy, the sectoral energy intensity was the main driver of reductions in primary energy use. Improvements of energy intensity, particularly after 2004, were caused by the international crisis and high prices of oil and natural gas, to which the productive sectors responded with productivity gains, technological improvement and rise of prices of certain products (e.g. land transport).

In the case of the economic transition, the shift towards services had a modest effect in energy performance due to increases in non-productive energy uses (e.g. comfort) in this sector. In the case of the energy transition, the effect of a larger share of renewables depended on the primary equivalent energy accounting method for renewable energy. The partial substitution method led to a much lower effect of the energy sector, which reflected the improvements in primary-to-final efficiencies brought by the introduction of natural gas for power generation. On the other hand the physical content method led to a higher contribution of energy sector transitions since stresses the effect of shifts away from fossil carriers.

The results give insights on the most suitable areas for intervention to boost energy decoupling in the Portuguese economy:

The country should put emphasis on reduction of energy intensity in the service sector so the servicification of the economy benefits the overall energy performance. This can be achieved by energy efficiency, rational use of non-productive energy services and increasing competitiveness.

Other productive sectors, especially the industry, should put emphasis on energy efficiency and improvements in the productivity of energy services. In this respect, the demand for energy products with larger associated primary energy (i.e. electricity) can be justified if those products allow the use of much more energy efficient processes

The energy sector should focus on improvements in the aggregate primary-to-final conversion efficiency by technology progress and further substitution of oil-fuelled power generation for natural gas and renewables. In addition, it should support the penetration of renewables in other energy uses such as mechanical work for transportation services.

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References

L. Aguiar-Confraria, F. Alexandre, and M. C. Pinho. O euro e o crescimento da economia portuguesa: Uma análise contrafactual. *Análise Social*, (203): 298–321, 2012.

V. Alcántara and R. Duarte. Comparison of energy intensities in European Union countries: Results of a structural decomposition analysis. *Energy Policy*, 32(2):177–189, 2004.

J. Amador. Energy production and consumption in Portugal: Stylized facts. Report, Banco de Portugal, 2010.

J. Amador. Energy content in manufacturing exports: A cross-country analysis. *Energy Economics*, 34(4):1074–1081, 2012.

F. Amorim, M. V. M. Martins, and P. Pereira da Silva. A new perspective to account for renewables impacts in Portugal. In *7th International Conference on the European Energy Market*, pages 1–6, 2010.

I. Arto, C. Gallastegui, and A. Ansuategi. Accounting for early action in the European Union Emission Trading Scheme. *Energy Policy*, 37(10): 3914–3924, 2009.

BdP. *A economia portuguesa no contexto da integração económica, financeira e monetária*. Banco de Portugal, Lisboa, 2009.

Subhes C. Bhattacharyya. *Energy Economics: Concepts, Issues, Markets and Governance*. Springer, Dundee, 2011.

P. Brown. European Union wind and solar electricity policies: Overview and considerations. Report, Congressional Research Service, 2013.

C. Bullard and R. Herendeen. The energy cost of goods and services. *Energy Policy*, 3(4):268–278, 1975.

S. Claessens, D. Dell'Ariccia, G.and Igan, and L. Laeven. Cross-country experiences and policy implications from the global financial crisis. *Economic Policy*, 25(62):267–293, 2010.

H. A. Costa. From Europe as a model to Europe as austerity: The impact of the crisis on Portuguese trade unions. *Transfer: European Review of Labour and Research*, 18(4):397–410, 2012.

M. De Haan. A structural decomposition analysis of pollution in the Netherlands. *Economic Systems Research*, 13(2):181–196, 2001.

DGEG. Balanços energéticos (Online database), 2012. URL `http://www.dgeg.pt/`.

DGEG. Potência instalada nas centrais produtoras de energia elétrica 2008-2012 (Online database), 2014a. URL http://www.dgeg.pt/.

DGEG. Produção bruta de energia elétrica (Online database), 2014b. URL http://www.dgeg.pt/.

D. Diakoulaki and M. Mandaraka. Decomposition analysis for assessing the progress in decoupling industrial growth from CO2 emissions in the EU manufacturing sector. *Energy Economics*, 29(4):636–664, 2007.

E. Dietzenbacher and A. R. Hoen. Deflation of input-output tables from the user's point of view: A heuristic approach. *Review of Income and Wealth*, 44(1):111–122, 1998.

E. Dietzenbacher and B. Los. Structural decomposition techniques: Sense and sensitivity. *Economic Systems Research*, 10(4):307–324, 1998.

E. Dietzenbacher and U. Temurshoev. Input-output impact analysis in current or constant prices: does it matter? *Journal of Economic Structures*, 1(1):1–18, 2012.

EIA. Crude oil prices: Europe brent spot price FOB (dollars per barrel), 2014. URL http://www.eia.gov/.

EU. Directive 2009/28/ec of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. *Official Journal of the European Union*, 140(16):16–62, 2009.

EUROSTAT. Correspondence table NACE Rev. 2 - NACE Rev. 1.1. Report, European Comission, Feb 2014 2008.

EUROSTAT. Correspondence table CPA 2002 - CPA 2008. Report, European Comission, Feb 2014 2009.

EUROSTAT. ESA 95: Supply, use and input-output tables (Online database), 2014a. URL http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95_supply_use_input_tables/data/workbooks.

EUROSTAT. Gas prices for industrial consumers (Online database), 2014b. URL http://epp.eurostat.ec.europa.eu/.

M. Farto and H. Morais. A crise portuguesa, o resgate internacional e o crescimento económico: Notas e reflexões. *JANUS.NET e-journal of International Relations*, 2(1):124–132, 2011.

S. French, A. Leyshon, and N. Thrift. A very geographical crisis: The making and breaking of the 2007–2008 financial crisis. *Cambridge Journal of Regions, Economy and Society*, 2(2):287–302, 2009.

D. Gros. Macroeconomic imbalances in the Euro area: Symptom or cause of the crisis? *CEPS Policy Brief*, April(266):1–11, 2012.

Z. Guevara, T. Sousa, and T. Domingos. An approach for a better evaluation of energy efficiency trends using index decomposition analysis and useful work accounting. *Energy Economics (submitted)*, 2014.

R. Haas, Panzer C., Resch G., Ragwitz M., Reece G., and Held A. A historical review of promotion strategies for electricity from renewable energy sources in EU countries. *Renewable and Sustainable Energy Reviews*, 15(2):1003–1034, 2011.

K. Heer and O. Langniß. Promoting renewable energy sources in Portugal: Possible implications for China. Report, Centre for Solar Energy and Hydrogen Research, 2007.

S. T. Henriques. *Energy transitions, economic growth and structural change: Portugal in a long-run comparative perspective*, volume 54 of *Lund Studies in Economic History*. Lund University, Lund, 2011.

R. Hoekstra and J. C. J. M. van den Bergh. Structural decomposition analysis of physical flows in the economy. *Environmental and Resource Economics*, 23(3):357–378, 2002.

R. Hoekstra and J. C. J. M. van den Bergh. Comparing structural decomposition analysis and index. *Energy Economics*, 25(1):39–64, 2003.

IEA. Energy balances of OECD countries: Documentation for beyond 2020 files, 2011. URL `http://stats.oecd.org/`.

IEA. Natural gas information. Report, OECD Publishing, 2012.

IEA. What are the methods of calculation of primary energy equivalent?, 2014. URL `http://www.iea.org/statistics/`.

R. W. Jackson and A. T. Murray. Alternative input-output matrix updating formulations. *Economic Systems Research*, 16 (2):135–148, 2004.

A. N. Leite. A internacionalização da economia portuguesa. *Relações Internacionais*, (28):119–132, 2010.

N. Liu and B. W. Ang. Factors shaping aggregate energy intensity trend for industry: Energy intensity versus product mix. *Energy Economics*, 29(4): 609–635, 2007.

P. Lourtie. *Understanding Portugal in the context of the Euro crisis*. Peterson Institute for International Economics, Brussels, 2012.

E. Mata and Valério N. *História económica de Portugal: Uma perspectiva global*. Editorial Presença, Lisboa, 2nd ed. edition, 2003.

MEI. Decreto-lei n.º 71/2008. *Diário da República*, 1(74):2222–2226, 2008.

M. Mendiluce, I. Pérez-Arriaga, and C. Ocaña. Comparison of the evolution of energy intensity in Spain and in the EU15: Why is Spain different? *Energy Policy*, 38(1):639–645, 2010.

R. E. Miller and P. D. Blair. *Input-Output Analysis: Foundations and Extensions*. Cambridge University Press, Cambridge, UK, 2009. Second Edition.

M. Robaina Alves and V. Moutinho. Decomposition analysis and Innovative Accounting Approach for energy-related CO2 (carbon dioxide) emissions intensity over 1996–2009 in Portugal. *Energy*, 57(0):775–787, 2013.

J. Rodrigues and J. Reis. The asymmetries of European integration and the crisis of capitalism in Portugal. *Competition & Change*, 16(3):188–205, 2012.

J. F. D. Rodrigues and J. M. Rueda-Cantuche. A two-stage econometric method for the estimation of carbon multipliers with rectangular supply and use tables. *Ecological Economics*, 95:206–212, 2013.

A. Rose and S. Casler. Input–output structural decomposition analysis: A critical appraisal. *Economic Systems Research*, 8(1):33–62, 1996.

E. Rosenthal. Portugal gives itself a clean-energy makeover. *The New York Times*, 2010.

S. Seibel. Decomposition analysis of carbon dioxide emission changes in Germany: Conceptual framework and empirical results. Report, 2003.

A. Serrenho, T. Sousa, B. Warr, R. Ayres, and T. Domingos. Decomposition of useful work intensity: The EU-15 countries from 1960 to 2009. *Energy (submitted)*, 2014a.

A. Serrenho, B. Warr, T. Sousa, R. Ayres, and T. Domingos. Structure and dynamics of useful work along the agriculture-industry-services transition: Portugal from 1856 to 2009. *Ecological Economics (submitted)*, 2014b.

A. H. Strømman, G. P. Peters, and E. G. Hertwich. Approaches to correct for double counting in tiered hybrid life cycle inventories. *Journal of Cleaner Production*, 17(2):248–254, 2009.

B. Su and B. W. Ang. Structural decomposition analysis applied to energy and emissions: Some methodological developments. *Energy Economics*, 34 (1):177–188, 2012.

S. Suh. *Handbook of Input-Output Analysis Economics in Industrial Ecology.* Springer Verlag, New York, 2009.

T. Ten Raa and J. M. Rueda-Cantuche. The construction of input-output coefficients matrices in an axiomatic context: Some further considerations. *Economic Systems Research*, 15:439–455, 2003.

UN. *Concepts and methods in energy statistics with special reference to energy accounts and balances: A technical report.* United Nations, New York, 1982.

UN. *System of National Accounts 1993.* United Nations, New York, 1993.

UN. *Handbook of input-output table compilation and analysis.* United Nations, New York, 1999.

UN. *System of National Accounts 2008.* United Nations, New York, 2009.

S. Voigt, E. De Cian, M. Schymura, and E. Verdolini. Energy intensity developments in 40 major economies: Structural change or technology improvement? *Energy Economics*, 41(0):47–62, 2014.

U. Wachsmann, R. Wood, M. Lenzen, and R. Schaeffer. Structural decomposition of energy use in Brazil from 1970 to 1996. *Applied Energy*, 86(4): 578–587, 2009.

C. L. Weber. Measuring structural change and energy use: Decomposition of the US economy from 1997 to 2002. *Energy Policy*, 37(4):1561 – 1570, 2009.

B. Weidema, T. Ekvall, and R. Heijung. Guidelines for application of deepened and broadened LCA. Deliverable D18, CALCAS Project, 2009. http://www.calcasproject.net/.