Doctoral dissertation

Three Essays on the Economic Analysis of Energy Efficiency

by

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Table of Contents

Chapter II: A model for the competitive benchmarking of energy costs.

Chapter III: The increase of energy efficiency and the economy-wide rebound effect: A Computable General Equilibrium analysis for Spain.

An introduction and guide to the thesis

The excessive consumption of energy has become a major economic and environmental concern in many countries over the last two decades. Thus, the improvement in the efficient use of energy by firms and consumers, and the promotion of energy savings are at the top of the economic and environmental agenda in many countries. It has received particular attention in the European Union, where a considerable number of Directives and other legislative initiatives have been passed in the last two decades (e.g. EC 2006, EC 2012). Today, energy efficiency constitutes one of the cornerstones of the European Union’s 2020 strategy (EC, 2010).

Energy efficiency is undoubtedly in spotlight due to its strategic importance to the agenda of competitive and sustainable economic growth. Energy is considered a significant factor of production in sustainable economic development. Organizations and agencies from different countries, regularly prepare comprehensive analyses and reports highlighting the impacts of energy efficiency on the economy. Particularly it is often argued that energy efficiency improvements may act as a driver to boost economic growth and employment (IEA 2014, Vivideconomics 2013). The International Energy Agency (IEA 2014) has recently published a comprehensive report on the multiple benefits that the improvement of energy efficiency brings. In addition to the environmental benefits and the improvement of the health and welfare of citizens, it highlights its positive impact on economic growth and employment. The report includes a review of the main studies that provide empirical evidence of these impacts (e.g. Copenhagen Economics 2012, Barker and Foxon 2008, Lehr et al. 2012, Allan et al. 2006, ACE 2000).

Finally, the latest increase of energy prices, particularly in Europe, and the increasing impact of energy costs on industrial competitiveness have further encouraged the need of generating goods and services with less consumption of energy (IEA 2013, Deloitte 2010, EC 2014).

Reducing energy consumption is therefore a major challenge of the energy policy in most countries. This goal is particularly urgent in the case of Spanish economy, which registers higher energy intensity and dependence rates in relation to neighboring countries, while showing an increasing level of greenhouse gas emissions. Such concerns are reflected in the successively approved National Energy Efficiency Action Plans (MITYC 2007, 2011).

There is a wide variety of studies that analyze the energy intensity (i.e. the energy consumption per unit of GDP) in Spain from different perspectives (e.g. Roca and Alcántara 1996, Ramos-Martín 2003, Alcántara and Duarte 2004, Marrero and Ramos-Real 2008, Economics for Energy 2010, Mendiluce et al. 2010, Mendiluce 2012). Although there are some differences in the magnitude of their estimates, largely due to differences in the sources and variables, the type of deflators, the time periods, the industries considered, the level of sectoral disaggregation, and the methodological approaches, in general, all of them show that Spain traditionally consumes more energy per unit of output generated than most developed European economies.

In fact, from the 1970s energy intensity experienced a general reduction in developed countries, but in Spain this indicator continued to increase until 2005. Economics for Energy (2010) estimates that the energy intensity of the Spanish economy increased by 10% between 1990 and 2005, with the subsequent 54% in greenhouse gas emissions. In 2005, there was a change in the trend and since then there has been a decreasing trend, in line with that observed in the rest of the countries of our geographic and economic environment. However, Economics for Energy (2010) notes that in 2008 Spain's energy intensity was still 19% higher than that of the EU-15, which means that an additional 28 tonnes of oil equivalent was needed to produce one million Euro than the EU-15 average.

In the same vein, the contention of energy costs is seen as a priority to improve the competitiveness of Spanish manufacturing firms (MITYC, 2010). Actually, the share of energy costs on value added has increased relatively more than in those countries that are considered as the main exporting markets, and thereby eroding the competitiveness of manufacturing firms (Arocena and Díaz 2014).

This thesis addresses some of the issues referred to above. Thus, besides this introduction, the thesis is structured in three different essays, with the energy intensity and efficiency as a common thread. Each chapter is self-contained and can be read independently. Likewise, each one includes specific conclusions as well as their own reference list. The three papers aims to contribute to the academic literature, but they also aim to contribute to the current energy policy and economic debate outlined above. The analysis have managerial implications and are all policy relevant.

Chapter 1 focuses on the analysis of the energy intensity change. A country's energy performance is typically proxied by the rate of aggregate energy intensity, calculated as the ratio of energy consumed to GDP. The index number decomposition analysis is the usual approach to analyze the changes in a country's aggregate energy intensity. In this paper we propose an approach that combines the traditional index decomposition analysis with non-parametric frontier efficiency methods to decompose the energy intensity change. The suggested decomposition has the advantage of providing a more detailed number of determinants as well as allowing an integrated analysis of the relationship between energy efficiency and energy intensity.

We have applied the proposed decomposition to the analysis of the evolution of energy intensity in Spanish manufacturing over the period 1999-2007 by using regional and industry level data. Broadly, our findings confirm that the technical progress, the change in the input mix and the improvement in the level of technical energy efficiency are the factors that have contributed to reduce the energy intensity in most manufacturing industries throughout the analyzed period. By contrast, the increase in the scale of operations and the change in the regional distribution of production have acted as energy intensity increasing forces within most industries.

Our analysis can be of help to the industrial policy assessment by identifying the driving forces that contribute to decline the energy intensity at industry level, and thereby guiding policy makers in the design of alternative measures and incentives to further reduce the energy consumption in different industries. Thus, in the light of our results, in some industries (e.g. Textile) bringing policy measures aimed at incentivizing a better energy management and the adoption of changes in their capital-labor ratio would be particularly suitable to reduce the consumption of energy. By contrast, in other industries (e.g. Non-metallic mineral products, Basic metals) the application of a different package of measures are expected to be more effective (e.g. giving stronger incentives to increase the production in smaller firms, to introduce changes in the degree of vertical integration, to stimulate the production in certain regions).

Chapter 2 focuses on the analysis of energy costs and business competitiveness. In recent times energy has come to occupy a prominent place in the debate on business competitiveness, especially for those industrial activities where the energy bill constitutes a significant component of their production costs. Most studies conducting relative comparisons of energy costs are made at macro and sectoral levels, generally involving comparisons of the ratio of energy costs on value added, the ratio of energy costs on total production costs, or the unit energy cost across time and countries (e.g. EC, 2014b; Arocena and Díaz 2014).

In this paper, we propose a framework for benchmarking energy costs at firm level. Specifically we develop a unit energy cost frontier approach based on the Konüs framework introduced by Grifell-Tatjé and Lovell (2015) to the interfirm comparison of energy costs. The model allows decomposing the energy cost gap between two firms, the gap being the differential or variance between the energy cost of a benchmarking producer and the energy cost of a target firm in the sample. The cost gap is decomposed into five constituent accounting for different sources of the observed energy cost variance between two firms: energy price effect, non-energy inputs price effect, energy efficiency effect, vertical integration effect and scale effect. We illustrate the implementation and the usefulness of the decomposition with the benchmarking analysis of the unit energy cost variance of a sample of Chilean cement firms.

The decomposition proposed is useful for the firm managers first to assess company's energy performance of a company in comparison with firms' direct competitors. Further, it is useful because identifies the nature and quantifies the magnitude of the drivers that are behind the energy cost discrepancies. Therefore, it helps to clarify the areas of intervention of the management to improve energy performance. Thus, some sources are beyond the full control of the managers (largely input prices), while others are fully manageable. Further, some of them are readily manageable in the short run (e.g. energy efficiency), while others require long-run adjustments (e.g. vertical integration effect, activity effect).

From a public policy perspective, the identification of the energy cost drivers and its relevance can be of help to orientate structural reforms and other industrial policies. For instance, benchmarking results on the vertical integration and activity effects can eventually have implications for the public support of mergers and acquisitions intended to foster the vertical and horizontal consolidation of the industry. Likewise, the presence of substantial cost gaps due to energy price and energy efficiency effects may lead to public decision makers to consider investments in infrastructures to reduce energy prices or to improve logistics and transportation, and thereby reducing energy consumption.

Chapter 3 focuses on the consequences that an improvement of the energy productivity has for the Spanish economy. Specifically, the analysis aims to investigate the relationship between the enhancement of energy productivity and its impact on actual energy consumption. Putting differently, to estimate what is known as rebound effect, which refers to the possibility that technically possible energy savings are eroded by producers and consumers' economic responses. Rebound effects occur when reductions in energy consumption due to increased efficiency are partially offset by increased demand for energy, due to the system-wide response to falling effective energy prices.

To that effect, we formulate a computable general equilibrium (CGE) model to study the economy-wide effects of an increase of energy efficiency in the Spanish economy. Our model describes an open economy, disaggregated into 27 production sectors. The simulations consist in improving the productivity of energy-related inputs. Specifically, it is simulated a reduction of the use of 4 energy intermediate inputs (electricity, gas, oil refining and coal) by unity of output produced. We simulate a number of alternative scenarios and model specifications in order to estimate the rebound effect across sectors and energy types, as well as the impact on economic growth and employment.

The simulation with our base case scenario shows that a 5% improvement in energy efficiency in non-energy productive sectors would result in an actual reduction lower than 5%. Specifically, electricity would be reduced by 2.34%, the consumption of gas by 2.01%, oil refining products by 1.90%, and the demand of coal would fall by 1.76%. Therefore, our results show different magnitude of the rebound effect according to the type of energy: 53.2% for electricity, 59.7% for gas, 61.9% for petroleum products, and 64.8% for coal.

Likewise our estimates shows that when simulating a 5% increase of efficiency in the final use of energy by households the total household energy consumption would be reduced by 3.67%, indicating a rebound effect of 26.5%.

Regarding the macroeconomic variables, GDP increases by 0.61%, employment grows by 0.45% and unemployment decreases by 4.44%. In all sectors, except in the energy sectors, the expansion of the economy generates additional final demand energy use. However, despite the expansionary effect of the productivity improvement, there is a reduction in the quantity of energy consumed in the economy.

In Spain, the Energy Savings and Energy Efficiency Plan 2011-2020 mentions the possibility that there would have been some rebound effects on energy consumption in homes and public lighting when assessing the energy savings achieved in these sectors attributable to measures included in previous action plans (MITYC, 2011, pp. 71-75). However, these effects are not quantified and are not taken into account in setting energy saving targets for 2020.

If the magnitude of the rebound effect is not recognized, it is difficult to consider the importance of implementing measures to mitigate it. In this sense, there are instruments and intervention policies in different areas: policies that promote changes in consumer behavior, promotion of sustainable lifestyles, fiscal instruments (e.g. energy taxes and emissions), incentives to eco-technological innovation, non-fiscal measures to increase the effective price of energy services, or the development of new business models.

Finally, we must not forget that the same forces that trigger the rebound effect are also driving economic growth. Therefore, to the extent that any mitigating measures of the rebound effect act as forces reducing demand, both objectives seem a priori difficult to reconcile. From the point of view of the public decision maker, therefore, the challenge is to design and implement policies aimed at mitigating the rebound effect that are compatible with economic growth.

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Chapter 1.

A decomposition of the sources of the aggregate energy intensity change

1. Introduction

An economy's energy performance is typically proxied by the rate of the aggregate energy intensity, calculated as the ratio of energy consumed to GDP. Thus, the evolution of the energy intensity is seen as a direct indicator of the relationship between economic growth and energy use, and specifically, to identify whether there is a decoupling of energy consumption from economic growth. Note however that a decrease in energy intensity is not a synonym of energy savings or of lower energy consumption in absolute terms. A decrease in energy intensity may also occur if energy consumption grows at a lower rate than GDP, which is known as relative decoupling.

Hence, it is important to determine the factors that influence the evolution of the energy intensity. To that end, energy researchers have developed a number of index decomposition methodologies in the last decades. In essence, the most widespread way of decomposing the change of the energy intensity index with this approach allows decomposing the change in the aggregate energy intensity into two types of components: the structural effect (sometimes called product mix or compositional effect), and the sectoral energy intensity effect (often called intrasectoral energy intensity or efficiency effect).

The traditional index decomposition approach has however a fairly limited analytic power to assess the effect of a number of factors that are critical to understand the variation of energy productivity rates within an industry, such as the improvement in the technical energy efficiency or the reduction of waste in the use of energy, the technical progress, the change in the degree of vertical integration and capital-labor ratio, the change in the scale of operations, and the variation in the spatial arrangement of production.

In this chapter we provide a decomposition analysis of the energy intensity change that combines frontier efficiency methods with the conventional index decomposition approach. The proposed approach allows the identification of a more comprehensive set of factors that explain the observed variation in energy intensity. Furthermore, it addresses the analysis of energy efficiency as an integral part of energy intensity. We apply this framework to identify the sources of the variation of energy intensity in Spanish manufacturing between 1999 and 2007.

The rest of the paper is organized as follows. Section 2 reviews the relevant literature on energy intensity. Section 3 develops the decomposition of the energy intensity change. Section 4 describes the methods employed to implement the decomposition. Section 5 presents the data and variables employed in the analysis. The results are discussed in Section 6. Conclusions and final remarks are commented in Section 7.

2. Energy intensity and energy efficiency

As stated above, the energy-to-GDP ratio, referred to as energy intensity, is the most popular measure used in energy efficiency studies. Actually, the change of the energy intensity ratio is not strictly a measure of the change of energy efficiency, but the change in the reciprocal of the energy productivity ratio. Such distinction will be made clear later.

In any case, the index decomposition analysis (IDA) is the usual approach to quantify the underlying factors that contribute to changes in energy intensity, energy consumption, and related CO_2 emissions over time.[1] Since the late 1970s, a variety of index decomposition methods have been developed in the energy and environmental fields. The earliest studies were based on Laspeyres, Paasche,

[1] An alternative approach is the structural decomposition approach (SDA), which uses the input–output table as a basis for decomposition. Reviews of SDA can be found in Su and Ang (2012), Hoekstra and van den Bergh (2003).

Marschall-Edgeworth, and Fisher ideal indexes. Boyd et al. (1988) pioneered the index decomposition based on the Divisia index, and introduced the so-called arithmetic mean Divisia index method. Ang and Zhang (2000) and Ang (1995, 2004a) provide comprehensive surveys of this earlier literature. However all these index approaches have the drawback of leaving a residual term, i.e. the product (or the sum) of the estimated factors is not exactly equal to the observed change in the aggregate, which complicates the interpretation of the results. Moreover, they are unable to handle zero values in the data set.

The logarithmic mean Divisia index (LMDI) method was introduced by Ang and Choi (1997), and since then has become by far the most popular IDA approach due to its superior properties and its ease in practical implementation. As demonstrated in various papers (Ang and Zhang, 2000; Ang and Liu, 2001; Ang, 2004b), the LMDI method jointly satisfies the factor reversal test and the time reversal test, it is robust to zero and negative values, and is perfect in decomposition (i.e. it ensures null residual terms). Further, the LMDI decomposition has both additive and multiplicative formulations (see Ang and Zhang, 2000; Ang 2004b, 2015 for detailed analysis on alternative LMDI models).

To illustrate the LMDI method, let us define the aggregate energy intensity of one country in period t as the ratio between the energy consumed (E) and the output (Y) obtained in year t, i.e.

$$I_t = \frac{E_t}{Y_t} \quad (1)$$

The aggregate energy intensity can be expressed as a summation of the sectoral data

$$I_t = \frac{E_t}{Y_t} = \sum_i \frac{E_{i,t}}{Y_{i,t}} \frac{Y_{i,t}}{Y_t} = \sum_i I_{i,t} S_{i,t} \qquad (2)$$

where E_t is the total energy consumption; $E_{i,t}$ is the energy consumption in sector i; Y_t is the aggregate output; $Y_{i,t}$ is the output of sector i; $I_{i,t}$ is the energy intensity of sector i and $S_{i,t} = Y_{i,t}/Y_t$ is the production share of sector i.

The change in the aggregate energy intensity between period 0 and 1 can be expressed as

$$dI = \frac{I_1}{I_0} \quad (3)$$

We apply the multiplicative LMDI-II model (Ang and Choi 1997; Ang and Liu, 2001) to decompose the aggregate energy intensity[2]:

$$dI = \frac{I_1}{I_0} = \left[exp\left(\sum_i w_i\, ln\left(\frac{I_{i,1}}{I_{i,0}}\right)\right)\right] \cdot \left[exp\left(\sum_i w_i\, ln\left(\frac{S_{i,1}}{S_{i,0}}\right)\right)\right] \quad (4)$$

where

$$w_i = \frac{L\left(\frac{E_{i,1}}{E_1}, \frac{E_{i,0}}{E_0}\right)}{\sum_i L\left(\frac{E_{i,1}}{E_1}, \frac{E_{i,0}}{E_0}\right)} \quad (5)$$

In (5) $E_{i,t}/E_t$ is the share of sector i in the aggregate energy consumption in period t, and L is the logarithmic mean function introduced by Vartia (1976) and Sato (1976), which is defined as[3]

$$L\left(\frac{E_{i,1}}{E_1}, \frac{E_{i,0}}{E_0}\right) = \frac{\frac{E_{i,1}}{E_1} - \frac{E_{i,0}}{E_0}}{ln\frac{E_{i,1}}{E_1} - ln\frac{E_{i,0}}{E_0}} \quad (6)$$

[2] Ang (2015) argues that the multiplicative model is the preferred model for decomposing intensity indicators, while the additive composition analysis procedure is more suited when used in conjunction with a quantity indicator. In any case, there exists a direct relationship between the additive and multiplicative decompositions (Ang, 2004b).

[3] The use of the logarithmic mean is more widespread than in the energy efficiency decomposition literature. Thus, its use in the analysis of price and quantity indexes is discussed in detail by Balk (2008), while Balk (2010) makes use of it in measuring productivity change.

The first component in (4) is the intensity effect, and measures the impact associated with changes in the energy intensity of individual sectors. The second component in (4) is the so-called structural effect, which accounts for the impact of the change in the sectoral composition of the economy, i.e. the variation in the share of each sector in total GDP.

The LMDI method has been widely used to decompose changes in energy intensity, energy consumption and energy-related carbon emissions in many countries (see e.g. Mulder and Groot, 2012; Fernández et al. 2013, 2014; Voigt et al. 2014 for recent applications). In the case of Spain a number of studies apply LMDI methods to analyze the energy intensity change of the whole country (Fernández-González et al. 2003; Mendiluce, 2007; Marrero and Ramos-Real, 2008; Mendiluce et al, 2010), and that of specific regions (e.g. Ansuategui and Arto, 2004; Colinet and Collado, 2015).

The efficient consumption of energy has been equally analyzed from the literature on efficiency and productivity measurement from a somehow different perspective. Basically, the measurement of efficiency is based on the idea of comparing the actual performance of an economic unit with respect to the optimum performance that technology allows. This technological boundary is not however directly observable, so it must be empirically estimated from the data. Therefore, the efficiency of a company is determined by comparing their performance with that of the best observed performers, which define the efficient frontier.

Filippini and Hunt (2015) relate this literature, which is firmly based on the economic foundations of production, with the concept of energy efficiency. There are many examples of energy efficiency studies that use the two dominant approaches in the field of efficiency measurement: the parametric Stochastic Frontier Analysis (SFA) and the non-parametric Data Envelopment Analysis (DEA). For instance, Filippini and Hunt (2011, 2012) and Orea et al. (2015) investigate the energy efficiency in various countries with stochastic frontier analysis, while Zhou and Ang (2008), and Zhou et al. (2008) provide examples of measuring the energy efficiency by means of linear programming techniques. In this chapter, we use Data Envelopment Analysis (DEA), because it presents some attractive features over the traditional cost function estimation. First, it is a frontier technique, which allows for inefficient behavior. Second, it is not necessary to impose a priori any functional form relative to the underlying technology (i.e. quadratic, translog, etc.). Third, specific benchmark frontiers are constructed for diversified and specialized utilities. This avoids a general assumption of parametric approaches: the definition and estimation of identical forms of cost functions regardless of whether outputs are jointly produced or separately produced. In the next section, we combine the LMDI decomposition referred to above with a non-parametric frontier efficiency approach.

3. Methodology

3.1 Decomposing firm's energy intensity change

Let us first define the energy intensity of firm[4] j in year t as the ratio between the energy that consumes (E_j) and the output (Y_j) obtained in year t, i.e.

$$I_{j,t} = \frac{E_{j,t}}{Y_{j,t}} \quad (7)$$

The observed change in the energy intensity of firm j between period 0 and 1, can then be expressed as

$$dI_j = \frac{I_{j,1}}{I_{j,0}} = \frac{\frac{E_{j,1}}{Y_{j,1}}}{\frac{E_{j,0}}{Y_{j,0}}} \quad (8)$$

We decompose the change in energy intensity in (8) as the product of three elements

[4] Here, we refer to the 'firm' as any producer or economic unit. The economic unit can equally refers to a region, as we do in our empirical application.

$$dI_j = \left[\frac{\frac{E_1}{E_1^*(y_1)}}{\frac{E_0}{E_0^*(y_0)}}\right] \cdot \left[\frac{E_1^*(y_0)}{E_0^*(y_0)}\right] \cdot \left[\frac{\frac{E_1^*(y_1)}{y_1}}{\frac{E_1^*(y_0)}{y_0}}\right] = EECH_j \cdot TCH_j \cdot SCH_j =$$
$$= Energy\ efficiency\ change \cdot Technical\ change\ effect \cdot Scale\ change\ effect \qquad (9)$$

The first component in brackets in (9) is the *Energy Efficiency Change* (*EECH*). This element is defined as the quotient of two ratios. The numerator represents the firm's energy efficiency in period 1, measured as the ratio of the observed energy consumption in period 1 (E_1) and the minimum (efficient) level of energy required to produce the observed output level in period 1, $E_1^*(y_1)$. A firm is energy efficient if this ratio is equal to one, whereas a value greater than 1 indicates an excessive consumption of energy in producing the current output level.

Similarly, the denominator captures the energy efficiency relative to period 0. Therefore, a value of $EECH_j$ lower (greater) than unity indicates that energy efficiency of firm *j* has increased (decreased) between year 0 and 1, and thereby has contributed to reduce (increase) the observed energy intensity rate of firm *j*.

The second component in (9) represents the *Technical Change effect* (*TCH*), measured at the output level of period 0. This term quantifies the variation in the energy intensity driven by the shift in the technology between period 0 and period 1. Thus, it compares the minimum amount of energy required to produce the output level y_0 in period 1, with the minimum quantity of energy that was needed in period 0 to produce the same output level. Therefore, a value of TCH_j lower (greater) than one indicates that technical progress (regress) has occurred between the two time periods, contributing to reduce the firm's energy intensity.

Finally, the third component in (9) is the *Scale Change effect* (SCH). This term accounts for the impact on the variation of energy intensity resulting from a change in the scale of operations, taking the technology of period 1 as a reference. Thus, it is defined as the ratio between the minimum quantity of energy per unit of output needed to produce y_1 in period 1, and the minimum energy quantity per unit of output needed to produce y_0 in the same period 1.

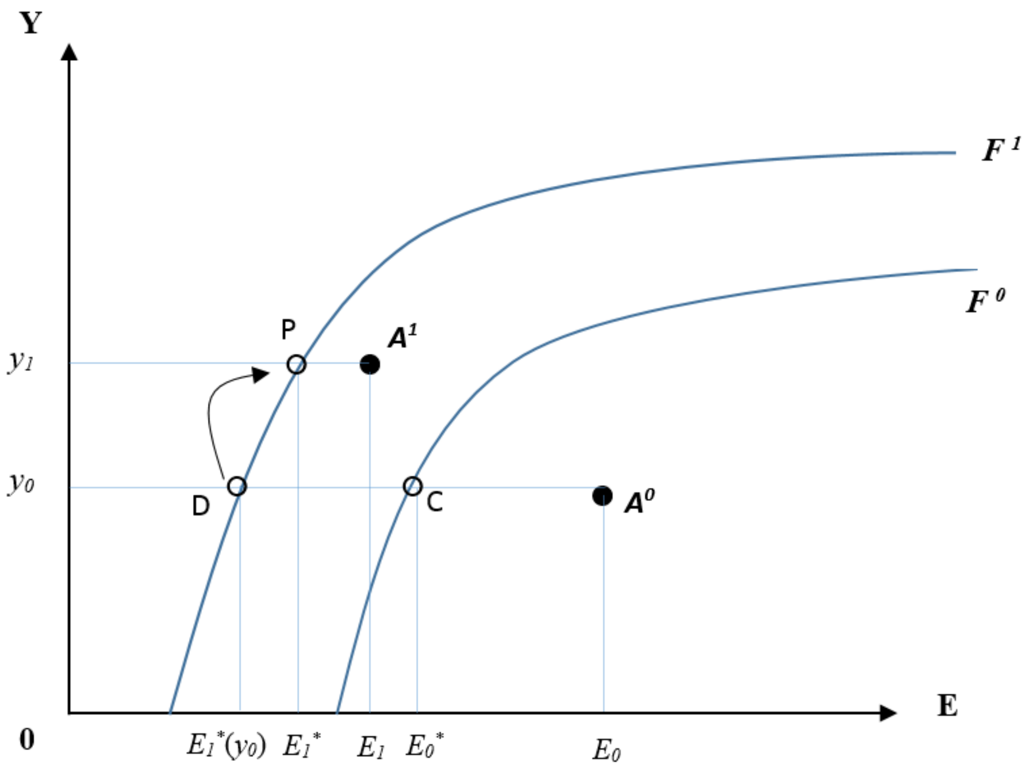
Figure 1 illustrates our decomposition in a single-(energy) input single-output case. The picture represents two production technologies prevailing in two different time periods. Particularly, the curve F^t represents the boundary (or frontier) of the production technology of period *t*. Thus, production frontier F^0 represents the minimum input that is required in period 0 to produce any given level of output or, alternatively, the maximum output that can be obtained in period 0 from any given input quantity.

The figure shows the observed output level and the energy consumption of firm *A* in period 0 (A^0) and period 1(A^1). Specifically, it reflects a situation where a decrease in the firm's energy intensity rate has occurred between period 0 and period 1 ($E_1/y_1 < E_0/y_0$). In this example, it is easy to see that part of the reduction in the intensity rate is due to the improvement of energy efficiency. The energy efficiency of firm *A* has improved because the observed energy consumption of firm *A* in period 1 (E_1) is closer to the efficient energy quantity E_1^*, denoted by point P in its contemporaneous production frontier (F^1), than what it was in period 0 (i.e. A^0 is relatively farther from the point C in F^0), and therefore *EECH* < 1.

Secondly, the upward shift of the production frontier reveals that a technological progress has occurred between the two time periods. Consequently the production of the output quantity y_0 requires a lower amount of energy in period 1 than the quantity that was needed in the previous period, i.e $E_1^*(y_0) < E_0^*(y_0)$, and therefore *TCH* = <1. In Figure 1, the energy savings due to the technical progress are represented by the horizontal distance between points D and C.

Finally, the impact of the change in the scale of operations on the variation of the energy intensity is reflected by the movement along the production frontier F^1 from point D (y_0, $E_1^*(y_0)$) to point P (y_1, E_1^*), which results in SECH < 1.

Figure 1. Decomposing the change in energy intensity



The Energy Efficiency Change (EECH) component in (9) can be further decomposed into two terms:

$$EECH = \frac{\frac{E_1}{E_1^*(y_1)}}{\frac{E_0}{E_0^*(y_0)}} = \left[\frac{\frac{E_1}{E_1'(y_1)}}{\frac{E_0}{E_0'(y_0)}}\right] \cdot \left[\frac{\frac{E_1'(y_1)}{E_1^*(y_1)}}{\frac{E_0'(y_0)}{E_0^*(y_0)}}\right]$$

$$= Technical\ efficiency\ change \cdot Input\ mix\ change \quad (10)$$

Therefore, the full decomposition of the energy intensity change of firm *j* can be formulated as

$$dI_j = \left[\frac{\frac{E_1}{E'_1(y_1)}}{\frac{E_0}{E'_0(y_0)}}\right] \cdot \left[\frac{\frac{E'_1(y_1)}{E^*_1(y_1)}}{\frac{E'_0(y_0)}{E^*_0(y_0)}}\right] \cdot \left[\frac{E^*_1(y_0)}{E^*_0(y_0)}\right] \cdot \left[\frac{\frac{E^*_1(y_1)}{y_1}}{\frac{E^*_1(y_0)}{y_0}}\right]$$

$$= TECH_j \cdot IMCH_j \cdot TCH_j \cdot SCH_j \qquad (11)$$

As Filippini and Hunt (2015) observe, there is not a unique and generally accepted definition of energy efficiency. Thus, a possible measure is the Farrell's radial input measure of technical efficiency (Farrell, 1957), in which the improvement of the level of efficiency requires a proportional reduction in both energy and the other inputs. However, we are interested in measuring the specific efficiency in the use of energy, and to that end in (10) we have introduced two different energy efficient benchmark quantities. To explain the differences between them, let us consider a KLEM model, which defines output as a function of capital (K), labor (L), energy (E) and other intermediate inputs (M). Other intermediate inputs (M) include materials (e.g raw materials and components) and services firms acquire to external suppliers.

In (10), *E´* denotes the minimum amount of energy that a firm requires to produce output *y*, while holding constant its current level of non-energy inputs (K, L and M). Therefore, the first component in brackets in (11), the technical efficiency effect ($TECH_j$), is a ratio of two measures of technical efficiency that captures the rate at which a firm reduces (or increases) the waste in the use of energy in its existing production process. Note that energy savings can only arise from an improvement in the management of the use of energy, but not from any substitution between inputs because non-energy inputs are not allowed to vary.

By contrast, *E** denotes the minimum amount of energy that can be achieved among all technically feasible input combinations that permit obtaining a given level of output. In other words, *E** is the quantity of energy that results from the least energy intensive feasible input bundle to produce output level *y*. Consequently, in calculating *E** any input substitution possibilities are allowed, and firms are allowed to fully adjust K, L and M in any direction, i.e. the observed quantities of K, L and M can either decrease or increase. Consequently, the element $IMCH_j$ in (11) captures the contribution of the change in the input mix to the observed energy intensity change between periods *t* and *t+1*. Specifically, a value of $IMCH_j$ lower (greater) than unity indicates that the input mix efficiency of firm *j* has increased (decreased) between year 0 and 1, and thereby has contributed to reduce (increase) the observed energy intensity rate of firm *j*.

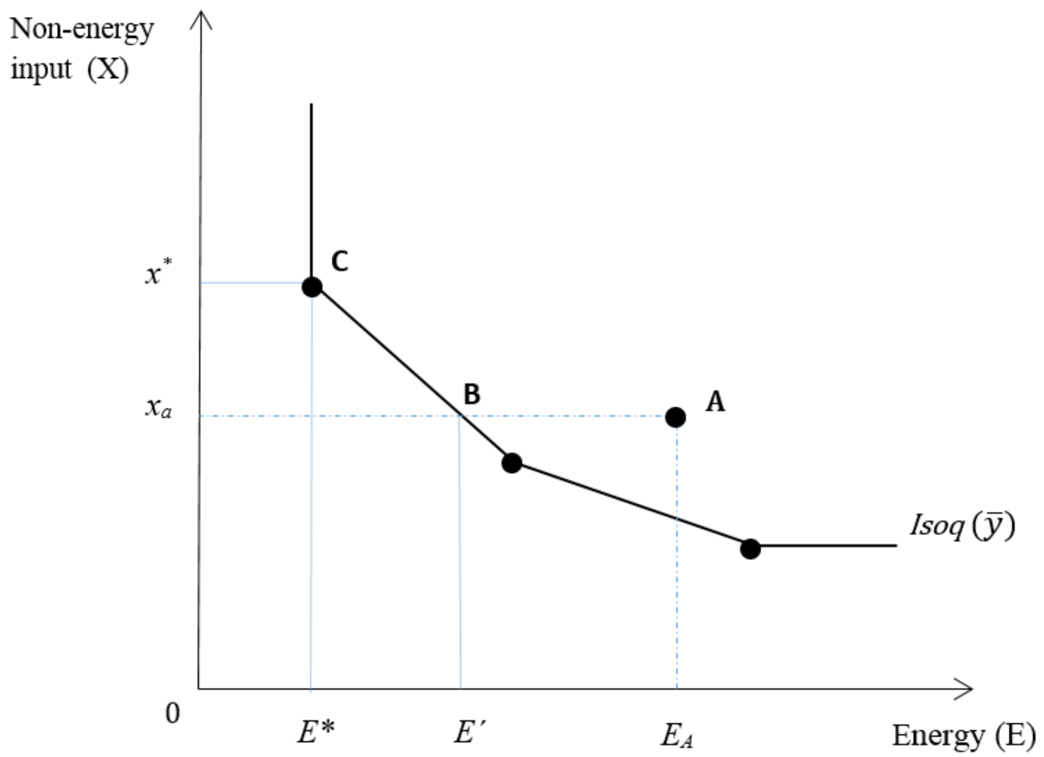
The distinction between *E'* and *E** is particularly relevant for the analysis of energy intensity because alternative combinations of non-energy inputs may result in substantial differences in energy consumption. On the one hand, the firm's energy consumption will be influenced by the capital-labor ratio *K/L*. In principle, one would expect that an increase of capital intensity would lead to higher energy consumption rates. For instance, the intensive use of equipment and the automation of production processes will typically require a higher amount of energy to produce certain goods than labor-intensive processes. In such case, it is said that capital and energy are complements. We note however that the effect of an increase of the *K/L* ratio can go either way, depending on the relationship between capital and energy (see e.g. Metcalf 2008, Song and Zheng 2012). Thus, if the increase of *K* is based on the replacement of capital stock by more energy efficient equipment then we should expect a decrease in the energy consumption. In this case energy and capital are substitutes.

On the other hand, for a given output level, the volume of the intermediate inputs *M* reflects the extent to which the activities are outsourced or conducted within the boundaries of the firm. In other words, it reflects the firm's buy or make decision, and thereby its degree of vertical integration. Let us consider two firms producing the same level of output but showing different levels of *M*. The firm with a low *M* would have internalized most of the value-creating activities associated with its business, consistent with a high level of vertical integration. In the case of a fully (perfectly) vertically integrated firm, $M = 0$. By contrast, a firm that procures most components and services externally would show a higher value of *M* and thus a lower degree of vertical integration. Broadly, we would expect that the lower the scope of vertical integration, the lower the energy intensity. In other words, a higher use of M is associated with a lower usage of both K and L, and thereby less energy consumption. Therefore, the ratio E'/E^{*} captures the energy savings that could be attained from changing the firm's degree of vertical integration and adjusting the capital-labor ratio.

Figure 2 illustrates the distinction between $E´$ and $E*$. The figure depicts a (piecewise linear) isoquant that shows the technically efficient combinations of two inputs, energy and other non-energy input, to produce a given level of output $\bar{y}$. Point A therefore represents a firm that is technically inefficient. Thus, $E´$ is the quantity of energy that results from the largest feasible contraction of the observed energy quantity, given the output level $\bar{y}$, and the quantity consumed of other non-energy inputs x_a. To reach the isoquant at point B, firm A should reduce its excessive consumption of energy by the proportion $E´/E_A$.

In Figure 2, company C has the input combination that uses the lowest quantity of energy to produce output level $\bar{y}$, tough requiring a higher quantity of the other non-energy input x. If the company A seeks to reduce its energy consumption below $E´$ it would require investing more on other inputs, up to $x*$. Accordingly, the difference between $E´$ and $E*$ accounts for the quantity of energy that could be saved if the company employs the lowest energy intensive input mix.

Figure 2. The measurement of energy efficiency



3.2 The sectoral energy intensity change

Let us first consider the energy intensity in a particular industry. The total sectoral output is generated in a number of *J* economic units. In our empirical application regions are the economic units under consideration. Thus, the output and the energy consumption in industry *i* are respectively the sum of the output and the sum of the energy consumed in the *J* different regions that make up the industry *i*. Thus, the sectoral intensity can be expressed as a summation of the regional data:

$$I_{i,t} = \frac{E_{it}}{Y_{it}} = \sum_{j} \frac{E_{ij,t}}{Y_{ij,t}} \frac{Y_{ij,t}}{Y_{it}} = \sum_{j} I_{ijt} R_{ij,t} \qquad (12)$$

where E_{it} denotes the total energy consumption in industry i in period t, Y_{it} is the total output of industry i in period t; $E_{ij,t}$ is the quantity of energy consumed in region j in the within the industry i; $Y_{ij,t}$ is the output of industry i produced in region j in period t, and R_{ij} denotes the share of region j in the total output of sector i.

Let us assume that the energy intensity of industry i varies from $I_{i,0}$ in period 0 to $I_{i,1}$ in period 1. We apply the logarithmic mean Divisia index presented in Section 2 to multiplicatively decompose the sectoral energy intensity change as:

$$d\mathrm{I}_{\mathrm{i,t}} = \frac{\mathrm{I}_{\mathrm{i,1}}}{\mathrm{I}_{\mathrm{i,0}}} = \left[exp\left(\sum\nolimits_{j} w_j\, ln\left(\frac{I_{j,1}}{I_{j,0}}\right)\right)\right] \cdot \left[exp\left(\sum\nolimits_{j} w_j\, ln\left(\frac{R_{j,1}}{R_{j,0}}\right)\right)\right] \qquad (13)$$

where the summation is taken over the J regions, and

$$w_j = \frac{L\left(e_j^1, e_j^0\right)}{\sum_j L\left(e_j^1, e_j^0\right)} \qquad (14)$$

In (14) $e_j = E_{i,j}/E_i$ is the share of region j on the total energy consumed in industry i, and L is the logarithmic mean function.

In expression (13) the change in sectoral energy intensity is expressed as the product of two elements. The first bracketed component in (13) captures the impact of the variation of regional energy intensity rates, while the second bracketed term captures the effect of the changes in the composition of the industry output. By introducing our decomposition of the regional energy intensity change as stated in (11) into the first bracketed term in (13) we obtain the decomposition of the energy intensity change in industry i as the product of five components:

$$
\begin{aligned}
d\mathrm{I}_{i,t} = \frac{\mathrm{I}_{i,1}}{\mathrm{I}_{i,0}} &= \left[exp\left(\sum\nolimits_{j} w_j \, ln\left(TECH_j\right)\right)\right] \cdot \left[exp\left(\sum\nolimits_{j} w_j \, ln\left(IMCH_j\right)\right)\right] \cdot \\
&\cdot \left[exp\left(\sum\nolimits_{j} w_j \, ln\left(TCH_j\right)\right)\right] \cdot \left[exp\left(\sum\nolimits_{j} w_j \, ln\left(SCH_j\right)\right)\right] \\
&\cdot \left[exp\left(\sum\nolimits_{j} w_j \, ln\left(\frac{R_{j,1}}{R_{j,0}}\right)\right)\right] \\
&= TECH_i \cdot IMCH_i \cdot TCH_i \cdot SCH_i \cdot REG_i \qquad (15)
\end{aligned}
$$

The last component in (15) is the regional effect (*REG*$_i$) and measures the impact of the changes in the distribution of the sectoral output among regions. A value of *REG*$_i$ lower (greater) than one indicates that production in industry *i* has moved from high (less) energy intensive regions to less (higher) energy intensive regions. The volume of production may increase in one region and decrease in others, and thereby increasing the share of the former on the total industry output. For instance, firms in one region may become more competitive and increase their production to the detriment of less competitive firms operating in other regions. Moreover, there are many reasons that may lead companies to move its activity from one region to another. For example, a specific region may offer economic advantages and more attractive conditions for business (e.g. lower labor costs, lower taxes, better infrastructures and services, higher availability of suppliers, etc). However, while there are factors that give a firm some competitive advantage of operating in certain region, taking advantage of such factors may require, at the same time, to incur in higher energy needs (e.g. due to the new firm's location, weather, process organization).

3.3 The aggregate energy intensity change

The manufacturing industry is an aggregate comprising a wide range of economic activities. Thus, the overall energy consumption in manufacturing is defined as the sum of the energy consumed in its $i = 1,\dots,M$ different sectors. Hence, the aggregate energy intensity rate in period *t* can be expressed as

$$I_t = \frac{E_t}{Y_t} = \sum_i \frac{E_{i,t}}{Y_{i,t}} \frac{Y_{i,t}}{Y_t} = \sum_i I_{i,t} S_{i,t} \qquad (16)$$

where E_t is the total energy consumption; $E_{i,t}$ is the energy consumption in industrial sector i; Y_t is the aggregate output; $Y_{i,t}$ is the output of industry i; $I_{i,t}$ is the energy intensity of sector i and $S_{i,t} = Y_{i,t}/Y_t$ is the production share of sector i.

By applying again the multiplicative LMDI decomposition the change in the aggregate energy intensity can then be expressed as

$$d\mathrm{I} = \frac{I_1}{I_0} = \left[exp\left(\sum_i w_i\, ln\left(\frac{I_{i,1}}{I_{i,0}}\right)\right)\right] \cdot \left[exp\left(\sum_i w_i\, ln\left(\frac{S_{i,1}}{S_{i,0}}\right)\right)\right] \qquad (17)$$

where

$$w_i = \frac{L(e_i^1, e_i^0)}{\sum_i L\left(e_i^1, e_i^0\right)} \qquad (18)$$

In (18) $e_i = E_{i,t}/E_t$ is the share of sector i in the aggregate energy consumption, and L is the logarithmic mean function defined above.

By introducing the decomposition of the sectoral energy intensity change as stated in expression (15) into (17), and denoting the variation in the output share of sector i as $SHARE_i = \frac{S_{i,1}}{S_{i,0}}$, we can express the full decomposition of the aggregate energy intensity change as

$$\begin{aligned} d\mathrm{I} = \frac{\mathrm{I}_1}{\mathrm{I}_0} &= \left[exp\left(\sum_i w_i\, ln(TECH_i)\right)\right] \cdot \left[exp\left(\sum_j w_j\, ln\left(IMCH_j\right)\right)\right] \cdot \\ &\cdot \left[exp\left(\sum_i w_i\, ln(TCH_i)\right)\right] \cdot \left[exp\left(\sum_i w_i\, ln(SCH_i)\right)\right] \\ &\cdot \left[exp\left(\sum_i w_i\, ln(REG_i)\right)\right] \cdot \left[exp\left(\sum_i w_i\, ln(SHARE_i)\right)\right] \\ &= TECH \cdot IMCH \cdot TCH \cdot SCH \cdot REG \cdot STR \qquad (19) \end{aligned}$$

The last element in expression (19) is the structural effect (*STR*), and captures the impact of the variation in the production structure on the aggregate energy intensity change. In other words, the structural change is associated with the varying growth rates among the constituent sectors of the aggregate industry, which lead to a change in its product mix. A value of *STR* lower than one indicates that production has shifted away from energy intensive industries.

4. Implementing the decomposition of the energy intensity rate change

In the decomposition formulated in (11), E_t and y_t are respectively the energy and output quantities observed in period t = 0,1. However, the efficient energy quantities $E_t^{'}$, E_t^{*}, $E_t^{*}(y_{t+1})$, $E_{t+1}^{*}(y_t)$ are not directly observed and must be estimated from the observed data and technologies. Technologies are also unobserved, so they must be estimated too. A production technology transforms inputs $x = (x_1, ..., x_n)$ into outputs $y = (y_1,..., y_m)$. The set of all input-output vectors that are feasible is called the production set (T), which is defined as

$$T = \{(x, y) \in \mathbb{R}_+^{n+m}: x \text{ can produce } y\} \quad (20)$$

We consider a piecewise linear sequential technology defined by the production set T^t as

$$T^t = \left\{(x,y): y \leq \sum_{s=1}^{t}\sum_{j=1}^{J} z_j^s y_j^s, x \geq \sum_{s=1}^{t}\sum_{j=1}^{J} z_j^s x_j^s, z_j^s \geq 0, \sum_{s=1}^{t}\sum_{j=1}^{J} z_j^s = 1\right\} \quad (21)$$

The technology defined in [21] is constructed in a sequential way, by accumulating information from previous years for each of the *J* firms (Tulkens and Vanden Eeckaut, 1995). Specifically, in the construction of period *t* technology we include data for all producers in *t* and all preceding years (from *s* =1 to *t*). This approach implies the assumption that the way in which production has been performed in the past is always feasible for the company in subsequent years; in other words, technological regress is not possible. The convexity constraint $\{z_i^s \geq 0, \Sigma z_i^s = 1\}$ in expression (21) allows defining a production technology with variable returns to scale (Banker *et al*. 1984).

In our empirical application, we assume that each firm produces only one output (m=1) and employs four inputs (n= 4), being the input vector x = (x_K, x_L, x_E, x_M). The input efficiency measure necessary to calculate the energy quantity $E_t'(y_t)$ is calculated as the solution to the following linear programming problem:

$$
\begin{aligned}
&\min \theta \\
&\text{s.t.} \\
&y^t \leq \sum_{s=1}^{t}\sum_{j=1}^{J} z_j^s y_j^s \\
&\sum_{s=1}^{t}\sum_{j=1}^{J} z_j^s x_{Ej}^s \leq \theta x_E^t \qquad\qquad (22) \\
&\sum_{s=1}^{t}\sum_{j=1}^{J} z_j^s x_{nj}^s = x_n^t \quad \text{n} = K, L, M \\
&\sum_{s=1}^{t}\sum_{j=1}^{J} z_j^s = 1 \\
&z_j^s \geq 0 \ \ \text{j} = 1, \ldots, J
\end{aligned}
$$

The solution of (22) is an input subvector measure of technical efficiency as defined in Färe et al (1994), where only the energy input x_E is scaled down and the other inputs are held constant at their observed levels. Thus, the efficient quantity of energy E_t' is given by

$$E_t' = \theta \cdot E_t \quad (23)$$

Similarly, $E_{t+1}'(y_{t+1})$ can be estimated as the solution to a linear programming problem identical to (22), just replacing period *t* data and technology with the corresponding *t+1* data and technology, i.e.

$$
\begin{aligned}
& \min \theta \\
& \text{s.t.} \\
& y^{t+1} \leq \sum_{s=1}^{t+1} \sum_{j=1}^{J} z_j^s y_j^s \\
& \sum_{s=1}^{t+1} \sum_{j=1}^{J} z_j^s x_{Ej}^s \leq \theta x_E^{t+1} \\
& \sum_{s=1}^{t+1} \sum_{j=1}^{J} z_j^s x_{nj}^s = x_n^{t+1} \qquad \mathrm{n} = K, L, M \\
& \sum_{s=1}^{t+1} \sum_{j=1}^{J} z_j^s = 1 \\
& z_j^s \geq 0 \;\; \mathrm{j} = 1, \ldots, J
\end{aligned}
\tag{22´}
$$

Finally, the maximum feasible shrinkage of the observed energy consumption (x_E) to produce y^t with period t technology is calculated as the solution to the following linear programming problem:

$$
\begin{aligned}
& \min \lambda \\
& \text{s.t.} \\
& y^{t} \leq \sum_{s=1}^{t} \sum_{j=1}^{J} z_j^s y_j^s \\
& \sum_{s=1}^{t} \sum_{j=1}^{J} z_j^s x_{Ej}^s \leq \lambda x_E^{t} \\
& \sum_{s=1}^{t} \sum_{j=1}^{J} z_j^s x_{nj}^s \geq 0 \;\; \mathrm{n} = K, L, M \\
& \sum_{s=1}^{t} \sum_{j=1}^{J} z_j^s = 1 \\
& z_j^s \geq 0 \;\; \mathrm{j} = 1, \ldots, J
\end{aligned}
\tag{23}
$$

Note that in (23) only the energy input (x_E) is scaled down, but unlike in (22), the use of capital (x_K), labor (x_L) and the intermediate inputs (x_M) is not constrained and can take any positive value. Consequently, the quantities of x_K, x_L, and x_M can decrease, increase or remain invariant with respect their observed level. Hence, the energy quantity E_t^* is the result of applying the largest feasible contraction of the energy input obtained from (23) to the observed energy quantity, i.e.

$$E_t^* = \lambda \cdot E_t \quad (24)$$

Similarly, $E_{t+1}^*(y_{t+1})$ can be estimated as the solution to a linear programming problem identical to [23], by just replacing period t data and technology with the corresponding $t+1$ data and technology, i.e.

$$\begin{aligned}
&\min \lambda \\
&\text{s.t.} \\
&y^{t+1} \le \sum_{s=1}^{t+1}\sum_{j=1}^{J} z_j^s y_j^s \\
&\sum_{s=1}^{t+1}\sum_{j=1}^{J} z_j^s x_{Ej}^s \le \lambda x_E^{t+1} \qquad (23') \\
&\sum_{s=1}^{t+1}\sum_{j=1}^{J} z_j^s x_{nj}^s \ge 0 \quad \mathrm{n} = K, L, M \\
&\sum_{s=1}^{t+1}\sum_{j=1}^{J} z_j^s = 1 \\
&z_j^s \ge 0 \quad \mathrm{j} = 1, \ldots, J
\end{aligned}$$

Finally, the energy efficiency measure needed to determine $E_{t+1}^*(y_t)$, i.e. the minimum feasible energy quantity to produce y^t with period $t+1$ technology, is determined as the solution to a problem identical to (23), but now using as reference the period $t+1$ technology:

$$\begin{aligned}
&\min \lambda \\
&\text{s.t.} \\
&y^{t} \le \sum_{s=1}^{t+1}\sum_{j=1}^{J} z_j^s y_j^s \\
&\sum_{s=1}^{t+1}\sum_{j=1}^{J} z_j^s x_{Ej}^s \le \lambda x_E^{t} \qquad (23'') \\
&\sum_{s=1}^{t+1}\sum_{j=1}^{J} z_j^s x_{nj}^s \ge 0 \quad \mathrm{n} = K, L, M \\
&\sum_{s=1}^{t+1}\sum_{j=1}^{J} z_j^s = 1 \\
&z_j^s \ge 0 \quad \mathrm{j} = 1, \ldots, J
\end{aligned}$$

5. Data and variables

We apply the decomposition model shown above to quantify the impact of the different factors that explain the evolution of the energy intensity observed in the Spanish manufacturing between 1999 and 2007. The manufacturing output is disaggregated into nine sectors, which are those defined in the Energy Balances of the International Energy Agency for most countries. Table 1 shows the sectoral breakdown with its corresponding National Classification of Economic Activity (NACE) codes. To be precise, the nine sectors considered in Table 1 roughly accounts for 95% of the manufacturing output in Spain. We have left out the sectors that are traditionally assorted under the heading of ‘Other manufacturing industries” (NACE codes 22, 31 and 32), due to the lack of reliable information on energy consumption in those industries.

Table 1. Classification of manufacturing industries

	NACE codes	*Energy intensity (E/Y)*
Food, beverages and tobacco	10,11,12	0.045
Textile and leather	13,14,15	0.067
Wood and wood products	16	0.139
Paper, pulp and printing	17, 18	0.114
Chemical and pharmaceutical products	20, 21	0.123
Non-metallic mineral products	23	0.323
Basic metals	24	0.284
Machinery and equipment	25,26,27,28	0.019
Transport equipment	29, 30	0.016

The output of each industry is produced in seventeen regions. Nevertheless, we note that some less-industrialized regions show no production in certain industries. The sector with the smallest number of observations is the Transport equipment industry, whose total output is generated in thirteen regions.

We estimate separate production technologies for each industry from the observed input-output data to compute the energy efficiency measures for each region. As stated above, the frontier of each year is estimated sequentially from current and all previous (but not subsequent) data. In order to ensure a sufficient number of observations to estimate each of the annual production frontiers for the period 1999–2007, in the construction of the frontier corresponding to the first year (1999) we have accumulated information from the year 1994 to the year 1999.

In most analysis of energy intensity at macroeconomic level the production output is typically expressed in value added at basic prices. At macro level the costs of intermediate inputs cancel out against the gross income of delivering these inputs in the derivation of GDP. However, at industry level the intermediate deliveries do not cancel out. Thus, at industry level it is more appropriate the use of the gross production rather than value added as the output variable (EC, 2014). Further, as Hulten (2010) argues, the use of value added as industrial output variable "implies (improbably) that efficiency-enhancing improvements in technology exclude material and energy" (Hulten, 2010, p. 1004). Consequently, we use the gross production as the output variable in each industry.

In each region and industry the output is obtained from the utilization of four inputs: Capital, Labor, Energy and Materials. Data on Labor and Materials are readily available from the Industrial Companies Survey, conducted by the National Statistics Institute. Thus, labor quantity is measured by the number of worked hours, while Materials include the purchases of intermediate inputs and services consumed in the production process (excluding energy consumption) measured in constant 1995 euros.

To obtain the quantities of capital and energy used in each region and sector we need to operate a little further. The energy consumption (in thousands of tons of oil equivalent, ktoe) in each industry is available only at national level, being provided by the Spanish Institute for Diversification and Energy Savings (IDAE). By contrast, the energy expenditure is drawn from the Industrial Companies Survey both at sectoral and regional level. With this data we calculate the toes of energy consumed in each industry and region by proceeding in three steps. First, we draw from the Industrial Companies Survey the aggregate (national) expenditure on electricity, gas and other energies in each industry, and the quantities of final energy in physical units consumption in electricity, gas and other energies (mostly oil products and to a lesser extent, coal) from the IDAE. Secondly, we divide the total expense in each energy type and sector (electricity, gas and others) by its respective quantity consumed in physical units (ktoe). And so we get the national prices for each fuel and sector. We assume that within the same sector there are no differences in the price of electricity, gas and other energies across regions. Then, we divide the energy expenditure by its corresponding price to get the quantity of energy consumed in each sector and region.

For calculating the capital measure we also proceed in three steps. First, we extract from the Industrial Companies Survey the value of the depreciation expense for each region and industry. Second, we calculate the average depreciation rate applied in each industry from the data contained in the KLEMS database. Finally, we divide the depreciation expenses in each region by the sectoral average depreciation rate to get the regional capital stock in each sector.

The sectoral price indices employed to deflate the gross output and materials were obtained from the EU KLEMS database, while the price indices to deflate the capital stock series were drawn from the database provided by Fundación BBVA.

Table 1 shows the mean values of the energy intensity by sector, revealing substantial differences in the energy intensity across industries. Thus, the most energy intensive industries are the Non-metallic mineral products and the Basic Metals, which use much more energy than the other industries to produce one unit of output. On the contrary, the Transport equipment and Machinery & equipment sectors are the less energy intensive consumers.

6. Results

Table 2 shows the results of our decomposition of the energy intensity change for the entire manufacturing industry between 1999 and 2007. First column in Table 2 reports the observed annual change in energy intensity, while columns (2) to (7) show the yearly changes for the six components identified in equation (19). Last row in each column shows the change rate of every factor in cumulative terms from 1999 to 2007. Figure 3 displays the evolution of the cumulative change in the energy intensity and its components over the period under consideration.

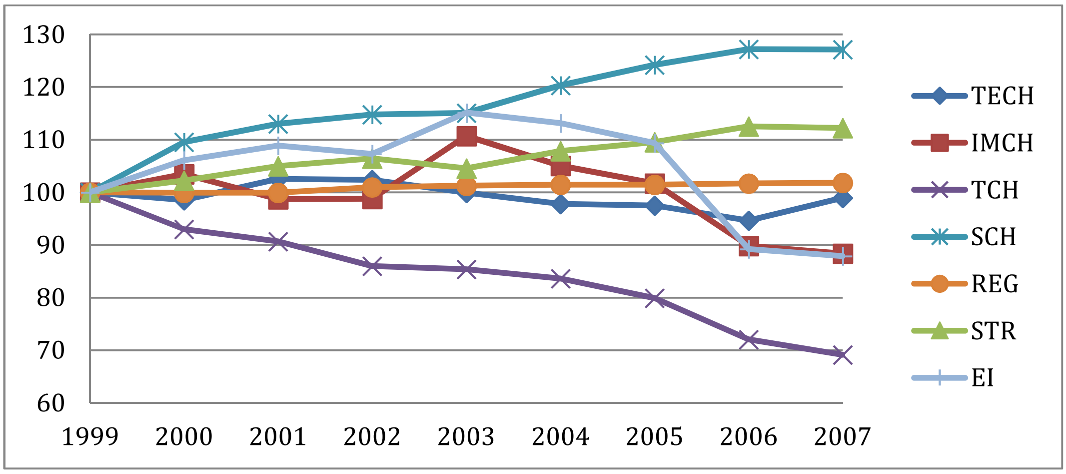
Table 2. The energy intensity change and its components (total manufacturing sector)

	(1) *d*I	(2) TECH	(3) IMCH	(4) TCH	(5) SCH	(6) REG	(7) STR
1999/00	1.061	0.985	1.035	0.930	1.096	1.000	1.022
2000/01	1.026	1.041	0.954	0.975	1.032	1.000	1.027
2001/02	0.986	0.998	1.001	0.949	1.015	1.010	1.014
2002/03	1.073	0.976	1.120	0.993	1.003	1.003	0.983
2003/04	0.983	0.979	0.949	0.979	1.046	1.002	1.031
2004/05	0.967	0.997	0.968	0.955	1.032	0.999	1.016
2005/06	0.816	0.971	0.883	0.902	1.024	1.003	1.028
2006/07	0.985	1.046	0.984	0.959	0.999	1.001	0.997
1999/07	*0.879*	*0.990*	*0.884*	*0.691*	*1.271*	*1.018*	*1.123*

The number at the bottom of the first column in Table 2 is 0.879, indicating that the energy used per unit of output obtained in the aggregate manufacturing industry decreased by 12.1% between 1999 and 2007. A look at Figure 3 reveals that the energy intensity presents a cumulative growth until 2005, showing an abrupt reduction in 2006. A similar sharp decline in 2006 is reported in the official statistics (MICYT, 2006) relative to the overall Spain’s energy intensity (measured in toe per GDP).

As shown in column (4), such decline is primarily due to Technical Change, which would have reduced the energy intensity rate by 30.9%. Figure 3 confirms that a steady and significant technological progress occurred throughout the period. The second most important factor in reducing energy intensity has been the change in the input mix (IMCH). Thus, column (3) indicates that this effect would have led to a decrease of 11.6% in the manufacturing energy intensity. The results of the effect of the Technical Efficiency Change (EMCH) in column (2) suggests that only a slight improvement in the use of energy occurred within firms, which would have caused a cumulative positive effect of 1%.

Figure 3. The energy intensity change of manufacturing and its components (1999-2007)



However, the energy reducing effect of the aforementioned factors is partially offset by the evolution of the other three components. Above all others, the scale effect (SCH) reported in column (5) is notably higher than one, indicating that the increase in the scale of operations registered during the period in the manufacturing sector was accompanied by a much more intensive use of energy. Specifically, the energy intensity of manufacturing would have increased by 27.1% throughout the period due to the scale effect. Figure 3 displays the consistent and increasing trend of the scale effect since the beginning of the period under consideration.

Secondly, column (7) shows the impact of the change registered in the sectoral composition of the Spanish manufacturing industry throughout the analyzed period. Specifically, the Structural Effect (STR) would have contributed to rise the aggregate energy intensity of manufacturing by 12.3%, motivated by the increase of the share that the relatively higher energy-intensive activities have in the aggregate industrial output.

Thirdly, the Regional Effect (REG) in column (6) indicates that the variation in the distribution of the output across regions that occurred over the considered period would have increased the aggregate energy intensity by 1.8%.

Thus far we have discussed the general results for the aggregate manufacturing. Let us analyze now the results of individual industries. First of all, before discussing the results relative to the decomposition of the sectoral energy intensity change, we focus on the analysis of the level energy efficiency at sectoral level. Specifically, Table 3 shows the estimates of the two energy efficiency measures defined by the two linear programming problems (22) and (23), as well as the differences in the composition of the input vectors corresponding to both energy efficiency references. All figures in Table 3 are the mean values registered over the period 1999-2007.

The first column in Table 3 shows the value of the technical energy efficiency achieved in each industry over the period under consideration. That is, it shows the average value of θ that results from solving the linear programming problem written in (22) for every year. For instance, we note that the average technical energy efficiency in the Food industry is 0.848, indicating that the Food sector could reduce its consumption of energy by 15.2% without reducing output and holding fixed the observed levels of the other inputs.

Table 3. Energy efficiency. Mean values (1999-2007)

	$\theta = E'/E$	$\lambda = E^*/E'$	M^*/M	K^*/K	L^*/L
Food	0.848	0.754	1.008	0.671	0.867
Textile	0.961	0.800	1.017	0.764	0.963
Paper	0.777	0.562	0.977	0.751	1.154
Chemical	0.814	0.630	0.998	0.751	1.057
Non-metallic mineral products	0.934	0.737	1.057	0.782	0.933
Transport equipment	0.808	0.547	1.024	0.822	0.857
Wood	0.872	0.640	1.012	0.687	1.130
Basic Metals	0.931	0.580	1.043	0.901	1.154
Machinery and equipment	0.885	0.663	1.020	0.696	0.834

The second column in Table 4 lists the value of the input mix energy efficiency, i.e. the average value of λ that results from solving the linear programming problem written in (23) for every year. In the case of the Food industry the value of λ is 0.754. That is, the Food sector could further reduce the consumption of energy by 24.6%, if the optimal least energy demanding input mix is adopted, without reducing output.

The Textile industry appears to be the industry that achieves the highest energy efficiency, both regarding the technical efficiency (0.961) and the input mix efficiency (0.800). Conversely, our results suggest that in the Paper industry there is a large room for improvement in both efficiency dimensions.

Last three columns in Table 3 compare the energy-efficient input quantities associated to E^* (K^*, L^*, M^*) with the observed input quantities (K, L, M), which we recall are held fixed in computing the technically efficient energy quantity E'. That is, the ratios between the two show the changes that every sector should make in their input bundle to achieve the smallest energy consumption. In the case of the Food industry, the optimal mix would require a quantity of purchased intermediate inputs 0.8% greater than the quantity actually consumed, while using 32.9% less capital, and 13.3% less labor than their respective observed quantities.

Most industries reveal a fairly similar pattern: to achieve the smallest energy consumption it is required to increase the purchase of intermediate inputs and decrease the use of capital in a larger proportion than labor, resulting in a lower capital intensity of production. There is however some interesting exceptions. In some industries the increase of M is accompanied by an increase of labor (e.g. Basic Metals, Wood). In the Paper industry, and to a lesser extent in the Chemical sector, the energy efficient vector is associated with fewer purchases of materials and services. This suggests that in these manufactures, the processing of purchased raw materials and components needs more energy than the processing of internally made feedstock.

Table 4 and Figure 4 present the energy intensity change and its determinants for the nine manufacturing sectors considered in this study. In Table 4, the horizontal product of columns (1) to (5) equals the energy intensity change observed in 1999-2007 for each sector, which is reported in column (6).

Last column of Table 4 reveals that eight out of nine sectors improved its energy intensity over the period under consideration. Only the Chemical sector registered an increase of 9.7% in its energy intensity rate. The Basic Metals industry shows the largest reduction (42.1%), followed by the Textile industry (39%). Table 4 nevertheless shows notable disparities across sectors with respect to the sign and magnitude of the explanatory factors.

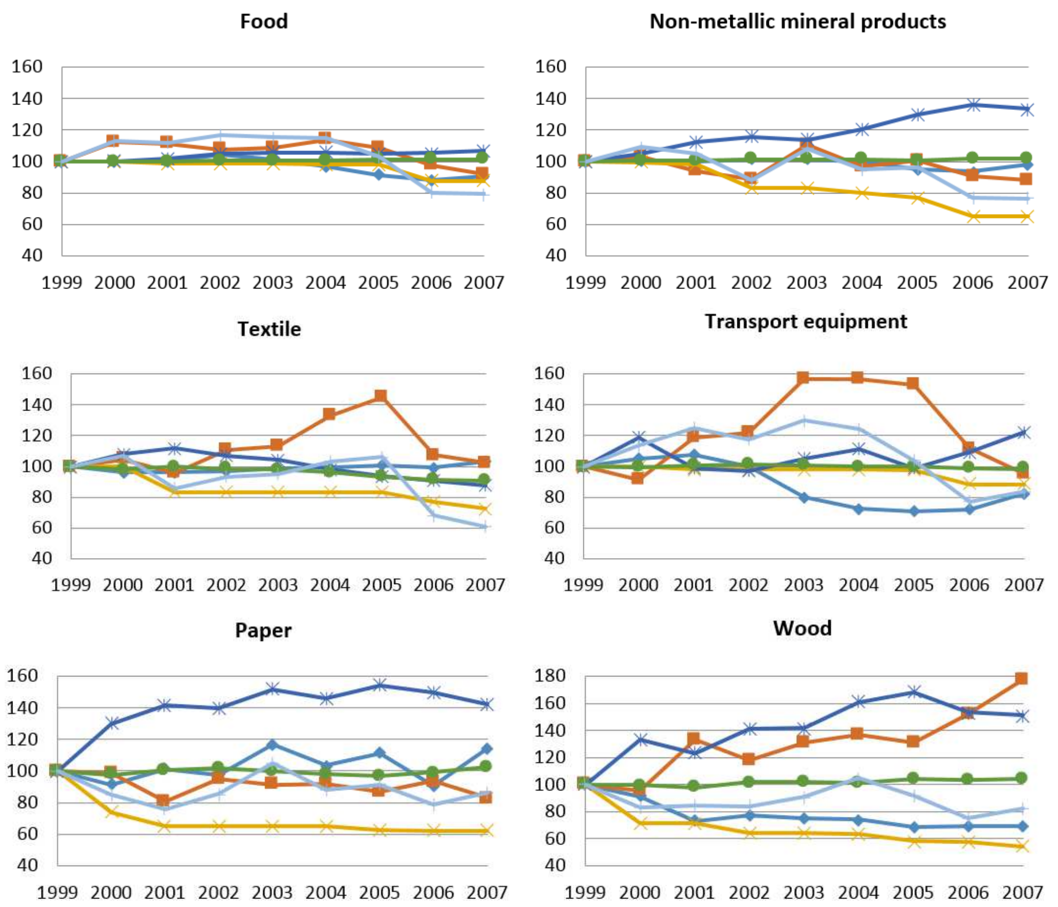
As shown in column (3), Technical Change is the main source of energy intensity reduction in most sectors. Nevertheless, in two industries (Chemical and Machinery & Equipment) the effect of the input mix change is the most important driver, as can be seen in column (2). Column (1) reveals that the improvement of technical energy efficiency is the dominant energy-reducing factor in the Transport Equipment industry, while Wood, Basic Metals and Food sectors also show important savings derived from this efficiency increase.

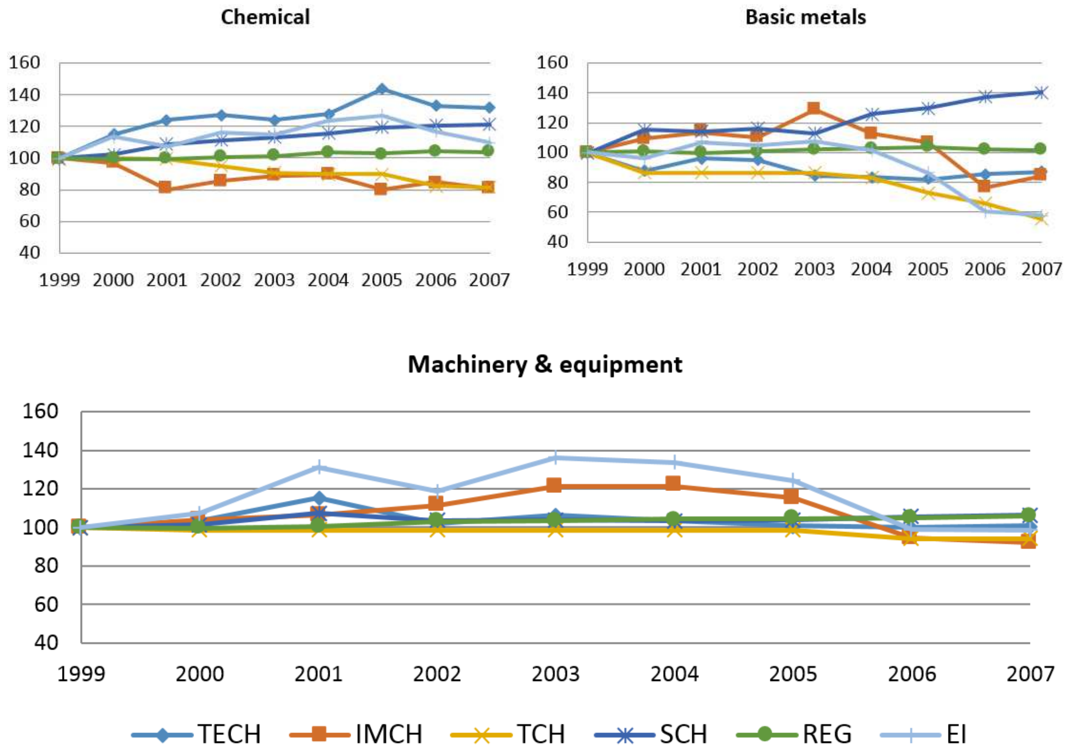
Table 4.The energy intensity change and its components across industries 1999-2007

	(1) TECH	(2) IMCH	(3) TCH	(4) SCH	(5) REG	(6) *d*I
Food	0.910	0.919	0.877	1.067	1.014	0.793
Textile	1.032	1.023	0.728	0.875	0.907	0.610
Paper	1.142	0.829	0.623	1.425	1.025	0.861
Chemical	1.320	0.807	0.817	1.213	1.040	1.097
Non-metallic mineral products	0.982	0.880	0.653	1.333	1.019	0.767
Transport equipment	0.824	0.953	0.884	1.225	0.984	0.837
Wood	0.725	1.327	0.545	1.512	1.043	0.827
Basic Metals	0.869	0.846	0.553	1.406	1.013	0.579
Machinery and equipment	1.009	0.919	0.942	1.066	1.058	0.984

As column (4) indicates, the scale change effect is the main negative force working against energy intensity. The sole exception is the Textile industry, where the change in the scale of operations had a positive impact of 12.3%. The period analyzed was a time of high sustained growth in Spain. The significantly negative scale effect detected in various industries indicates that such output increase required a proportionally higher consumption of energy, suggesting the presence of firm size inefficiencies within those industries with respect to the use of energy. Finally, with the exceptions of the Textile and Transport equipment sectors, the regional effect has contributed to deteriorate the energy intensity change. This suggests that in seven out of nine industries production has moved from less energy intensive regions to higher energy intensive regions.

Figure 4. The cumulative energy intensity change and its components





7. Conclusions

This chapter has presented a way to analyze the change in energy intensity that combines frontier methods and the index decomposition approached usually employed in energy studies. The suggested decomposition has the advantage of providing a more detailed number of determinants as well as allowing an integrated analysis of the relationship between energy efficiency and energy intensity.

We have applied the proposed decomposition to the analysis of the evolution of energy intensity in Spanish manufacturing over the period 1999-2007 by using regional and industry level data. Broadly, our findings confirm that the technical progress, the change in the input mix and the improvement in the level of technical energy efficiency are the factors that have contributed to reduce the energy intensity in most manufacturing industries throughout the analyzed period. By contrast, the increase in the scale of operations and the change in the regional distribution of production have acted as energy intensity increasing forces within most industries.

In any case, the individual results at regional level should be interpreted with caution due to the level of aggregation employed in defining the industries. Undoubtedly, the accuracy of frontier estimation and efficiency measures would be higher if we could observe data at the four-digit NACE level and give a more homogeneous definition of each industry.

Finally, in Spain, as in many other countries, the enhancement of energy efficiency and the reduction of energy consumption represent major economic and environmental challenges, as reflected in the successively approved National Energy Efficiency Action Plans (MITYC 2007, 2011). In such a context, our analysis can be of help to the industrial policy assessment by identifying the driving forces that contribute to decline the energy intensity at industry level, and thereby guiding policy makers in the design of alternative measures and incentives to further reduce the energy consumption in different industries. Thus, in the light of our results, in some industries (e.g. Textile) bringing policy measures aimed at incentivizing a better energy management and the adoption of changes in their capital-labor ratio would be particularly suitable to reduce the consumption of energy. By contrast, in other industries (e.g. Non-metallic mineral products, Basic metals) the application of a different package of measures are expected to be more effective (e.g. giving stronger incentives to increase the production in smaller firms, to introduce changes in the degree of vertical integration, to stimulate the production in certain regions).

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Chapter 2.

A model for the competitive benchmarking of energy costs

1. Introduction

In recent times energy has come to occupy a prominent place in the debate on business competitiveness. Many international agencies and public institutions have echoed the increasing impact of energy costs on industrial competitiveness (IEA 2013, EC 2014a,b).

Similar views are made from the business world. Thus, in a recent study by Deloitte (2010), the determinants of the global competitiveness of the industry, based on the analysis of the responses of more than 400 executives of manufacturing companies around the world, are identified. According to the executives interviewed, energy costs are perceived, along with innovation and labor costs and raw materials, as one of the fundamental pillars of the competitiveness of a country's manufacturing sector. In Europe, respondents rank energy costs and policies at the top of the list of ten key drivers of industrial competitiveness, behind talent-based innovation alone, ahead of the labor costs and raw materials. In the same vein, Eichhammer and Walz (2011) conclude that the competitiveness of a country's manufacturing sector, measured through an index that integrates various performance indicators, is inversely related to its energy intensity.

In short, the assessment of energy costs is considered a key managerial concern to gauge business competitiveness (McKinsey, 2009), particularly in those manufacturing firms that involve energy intensive processes, with energy costs accounting for a significant share of their costs of production.

Competitiveness is a relative concept, referring to the evaluation of the performance of one producer in relation to another. Relative performance evaluations or benchmarking, is the systematic comparison of the performance of one firm against other firms. More generally, as Bogetoft and Otto (2011, p.1) observe, it is comparison of production entities that transform the same type of resources to the same type of products and services. Therefore, any assessment of the competitive impact of one firm's energy costs requires some type of benchmarking against the role that energy costs mean to firm's competitors. That is to say, a company is more or less competitive in comparison with others that compete in the same industry.

Most studies conducting relative comparisons of energy costs are made at macro and sectoral levels. Generally they involve comparisons of the ratio of energy costs on value added, the ratio of energy costs on total production costs, or the unit energy cost across time and countries (e.g. EC, 2014b; Arocena and Díaz 2014). These studies often distinguish between the changes in real energy price (the monetary value paid by manufactures per unit of energy deflated with the sectoral value added deflator) and changes in energy intensity (the quantity of energy used per unit of value added in constant prices) to explain the unit energy cost changes observed in different sectors and countries.

In this paper, we propose a framework for benchmarking energy costs at firm level. Specifically we develop a unit energy cost frontier approach based on the Konüs framework introduced by Grifell-Tatjé and Lovell (2015) to the interfirm comparison of energy costs. The model allows decomposing the energy cost gap between two firms, the gap being the differential or variance between the energy cost of a benchmarking producer and the energy cost of a target firm in the sample. The cost gap is decomposed into five constituent accounting for different sources of the observed energy cost variance between two firms: energy price effect, non-energy inputs price effect, energy efficiency effect, vertical integration effect and scale effect. We illustrate the decomposition to benchmark the energy costs of a sample of Chilean cement firms that operate in a traditional energy intensive.

The rest of the paper is organized as follows. Section 2 presents the benchmarking model. Section 3 describes the methods to implement the decomposition. Section 4 presents the data and variables employed in the empirical application, and Section 5 discusses the results. Section 6 concludes the paper.

2. A model for benchmarking energy costs

Grifell-Tatjé and Lovell (2000, 2003, 2015) develop different strategies for analyzing productivity performance from a cost perspective. In this section we build on a Konüs ratio framework (Grifell-Tatjé and Lovell, 2015) to propose an interfirm unit energy cost benchmarking that allows to identify the sources of the difference in the energy cost performance between two firms.

We begin by introducing notation and terminology. Let $y = (y_1, \ldots, y_M) \in R_+^M$ be the output vector produced by means of the input vector $x = (x_1, \ldots, x_N) \in R_+^N$. Production technology can be represented by the input requirement set, which includes all input vectors yielding output y.

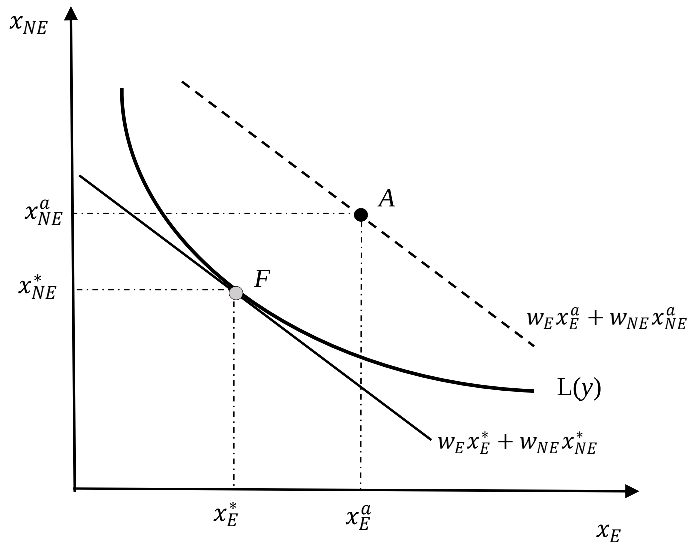
$$L(y) = \{\mathrm{x} : \mathrm{x\ can\ produce}\, y\}$$

Total cost is then $wx \geq C(y, w)$, where $C(y, w)$ is a cost frontier characterizing the minimum cost required to produce output y when input prices are w. We denote the cost-minimizing input vector as $x^* = (x_1^*, \ldots, x_N^*)$, and thereby the minimum cost can be expressed as $C(y, w) = wx^*$.

We designate x_E as the energy input, and w_E as the energy price. Then the energy expenditure is given by $w_E x_E \geq C_E(y, w)$, where $C_E(y, w)$ denotes the efficient energy cost. That is, $C_E(y, w) = w_E x_E^*$ being x_E^* the (total) cost-minimizing energy use.

Figure 1 illustrates these concepts. It shows the isoquant of the input requirement set L(y), which includes all feasible input combinations yielding output quantity y. The output is obtained from the utilization of two inputs: energy (x_E) and non-energy input (x_{NE}), with input prices w_E and w_{NE}, respectively. Consequently the isocost line with slope $-\frac{w_E^i}{w_{NE}^i}$ determines the cost-minimizing input mix (x_E^*, x_{NE}^*) at the tangency point F. Point A represents a firm that produces y with (x_E^a, x_{NE}^a) incurring a cost $w_E x_E^a + w_{NE} x_{NE}^a > w_E x_E^* + w_{NE} x_{NE}^*$.

Figure 1. Actual cost versus minimum cost



We observe a set of $i = 1, \dots, I$ firms. Our objective is to decompose the unit energy cost gap (*UECG*) or differential between the cost of producer *i* (*UEC*^{i}) and the unit energy cost of a benchmark competitor (*UEC*^{b}), defined as the ratio of the two observed unit energy costs:

$$UECG_b^i = \frac{UEC^i}{UEC^b} = \frac{\frac{w_E^i x_E^i}{y^i}}{\frac{w_E^b x_E^b}{y^b}} \quad (\mathbf{1})$$

where superscript '*b*' identifies the benchmark firm and superscript '*i*' the benchmarking firm *b*. Thus, y^i and y^b respectively denote the output produced by firm *i* and the benchmark firm *b*. In this paper we focus in the single output case, i.e. *y* is a scalar, for which there is a unique and readily identifiable unit cost measure. In the case of multiple-output production processes it would be required some kind of aggregation of the outputs into a single quantity index. We also note that (1) and the decomposition analysis that follows below can be instead applied to benchmarking the total cost gap $\left(\text{i.e.}\, w_E^i x_E^i / w_E^b x_E^b\right)$ in which case the presence of multiple output is not an issue. We decompose (1) as

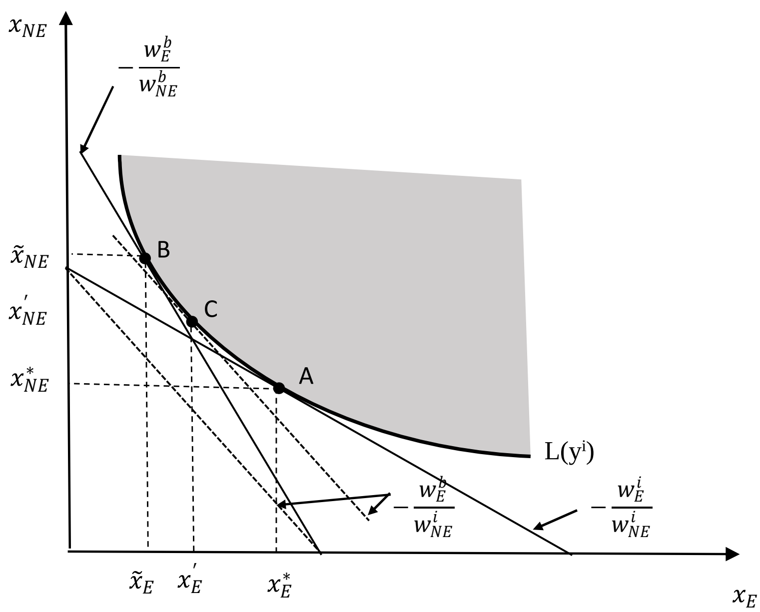
$$\begin{aligned} UECG_b^i = \frac{UEC^i}{UEC^b} = \frac{\frac{w_E^i x_E^i}{y^i}}{\frac{w_E^b x_E^b}{y^b}} = \\ \frac{C_E(y^i, w^i)}{C_E(y^i, w^b)} \; input\ price\ effect \\ \times \frac{w_E^i x_E^i / C_E(y^i, w^i)}{w_E^b x_E^b / C_E(y^b, w^b)} \; cost\ efficiency\ effect \quad (\mathbf{2}) \\ \times \frac{C_E(y^i, w^b)/y^i}{C_E(y^b, w^b)/y^b} \; activity\ effect \end{aligned}$$

The first component in (2) is the input price effect. It is a Konüs (1939) input price index that relates the optimal energy cost of firm *i* using its input price vector with the optimal energy cost that the same firm would incur if it had the input price vector of the benchmark firm. That is, it measures the impact of the input price change from w^i to w^b on the energy costs of producing output quantity y^i.

Figure 2 illustrates the input price effect. The picture shows the isoquant of the input requirement set L(y^i) that includes the input combinations yielding output quantity y^i, which is the output produced by firm i. The output is obtained from two inputs: energy (x_E) and non-energy input (x_{NE}), with input prices w_E^i and w_{NE}^i, respectively. Therefore firm i faces the isocost line with slope $-\frac{w_E^i}{w_{NE}^i}$ which determines the cost-minimizing input mix (x_E^{i*}, x_{NE}^{i*}) at point A.

A second isocost line reflects the input prices confronted by the benchmark firm (w_E^b, w_{NE}^b). Thus, the cost-efficient input combination to produce the output level y^i with benchmark firm's input prices is reached at tangency point B, with input quantities $(\tilde{x}_E, \tilde{x}_{NE})$. Therefore, the input price effect is measured by the ratio of the energy expenditure at point A and the energy expenditure at point B, i.e. $\frac{w_E^i x_E^{i*}}{w_E^b \tilde{x}_E}$.

Figure 2. The input price effect



The input price effect can be further decomposed as

$$Input\ price\ effect = \frac{C_E(y^i, w^i)}{C_E(y^i, w^b)} =$$

$$\frac{C_E(y^i, w^i)}{C_E(y^i, w_E^b, w_{NE}^i)}\ energy\ price\ effect \qquad (3)$$

$$\times \frac{C_E(y^i, w_E^b, w_{NE}^i)}{C_E(y^i, w^b)}\ non-energy\ inputs\ price\ effect$$

In (3) appears a new element: $C_E(y^i, w_E^b, w_{NE}^i)$, which measures the optimal energy cost to produce y^i with the energy price of the benchmark firm but holding the prices of the non-energy inputs of the firm *i*. Thus, the energy price effect in (3) measures the part of the input price effect that is solely due to the variance in energy prices between the firm *i* and the benchmark competitor. On the other hand, the second component in (3) measures the effect due to the discrepancy in the non-energy input prices between the two firms. Figure 2 illustrates both components.

In Figure 2 we have also included the isocost line corresponding to input prices (w_E^b, w_{NE}^i), represented by the dotted isocost line with slope $-\frac{w_E^b}{w_{NE}^i}$. Thus, the cost-efficient input combination to produce output level y^i with input prices (w_E^b, w_{NE}^i) is given by the tangency point C, which determines input quantities (x'_E, x'_{NE}). Therefore, the energy price effect is measured by the ratio of energy expenditure at A and the energy expenditure at C, i.e. $\frac{w_E^i x_E^{i*}}{w_E^i x'_E}$, while the non-energy price effect is measured by dividing the energy expenditure at C by the energy expenditure at point B, i.e. $\frac{w_E^i x'_E}{w_E^b \tilde{x}_E}$. To sum up:

$$Input\ price\ effect = \frac{w_E^i x_E^{i*}}{w_E^b \tilde{x}_E} = \underbrace{\frac{w_E^i x_E^{i*}}{w_E^i x_E'}}_{\substack{energy\ price\\ effect}} \times \underbrace{\frac{w_E^i x_E'}{w_E^b \tilde{x}_E}}_{\substack{non-energy\ price\\ effect}} \quad (4)$$

The second element in expression (2) is the cost efficiency effect, which compares the energy cost efficiency of firm *i*, defined as the ratio of the observed energy cost and the minimum energy cost, with that of the benchmark firm. A cost efficiency effect greater than 1 indicates therefore that firm *i* is less efficient than the benchmark firm, contributing to explain a poorer relative competitiveness. In other words, if both firms remove their respective cost inefficiency, firm *i* would shorten its energy cost gap with the benchmark firm.

We decompose the cost efficiency effect as

$$Cost\ efficiency\ effect = \frac{w_E^i x_E^i / C_E(y^i, w^i)}{w_E^b x_E^b / C_E(y^b, w^b)} =$$

$$\frac{w_E^i x_E^i / C_E(y^i, w^i; x_M^i)}{w_E^b x_E^b / C_E(y^b, w^b;\ x_M^b)} Energy\ efficiency\ effect \qquad (5)$$

$$\times \frac{C_E(y^i, w^i; x_M^i) / C_E(y^i, w^i)}{C_E(y^b, w^b;\ x_M^b) / C_E(y^b, w^b)} \quad Vertical\ integration\ effect$$

In (5) we introduce the cost frontier $C_E(y^i, w^i; x_M^i)$, which is a subvector cost function, measuring the minimum energy cost required to produce y^i with input prices w^i while keeping fixed the quantity of the intermediate input at its observed level (x_M^i). It is a kind of short-run cost function that emerges from the solution of the problem of minimizing total expenditure, under the constraints imposed by production technology, if we further assume that the quantity of some input (intermediate inputs x_M in this case) cannot be altered in the short-run.

For a given output quantity, the volume of the intermediate inputs x_M reflects the extent to which the activities are outsourced or conducted within the boundaries of the firm.[5] In other words, it reflects the firm's buy or make decision, and thereby its degree of outsourcing versus in-house production. Let us consider two firms (A and B) producing the same quantity of output. Firm A procures most components and services externally, while firm B produces them internally with a combination of capital, labor and energy. As a result, firm A shows a larger value of x_M than firm B. The degree of self-sufficiency in the procurement of intermediate inputs is relevant because it affects to firm's energy bill. Broadly, we would expect that the larger (lower) the level of outsourcing, the lower (higher) the energy requirements to produce the final output, and therefore the lower (higher) the energy costs.

For instance, in the cement manufacturing industry considered in our empirical illustration in Section 4, limestone and clay are the two most common raw materials used for cement production. A non-vertically integrated cement producer purchases these materials in the market from independent suppliers. By contrast, a backward vertically integrated firm extracts and prepares these materials from its own quarries, which requires additional energy consumption. Therefore, the energy bill of the vertically integrated cement manufacturer will be higher, while its expenditure on materials input will be lower than that of the less integrated firm.

The first component in (5) measures the impact on the energy cost gap attributable to differences in the efficiency in the use of energy between the two firms. Thus, the numerator of this component is a subvector measure of cost efficiency: it compares the actual with the minimum feasible energy expenditure of firm i given its current level of outsourcing. That is, the quantity of the intermediate inputs is not adjustable. The denominator defines a similar ratio for the benchmark firm.

[5] There are many studies that measure the degree of vertical (dis)integration as the ratio of intermediate inputs over total costs of production (e.g. Calabrese and Erbeta 2005, Pieri and Zaninotto, 2013 Devicienti et al, 2017), which is closely related to the classical and widely used ratio of value added to sales first proposed by Adelman (1955) to measure vertical integration.

The second component in (5) is the vertical integration effect and measures the energy cost gap due to differences in the outsourcing level. Thus, the numerator of this component compares the minimum feasible energy expenditure of firm *i* given its current level of intermediate inputs purchases with the minimum energy costs after adjusting the intermediate inputs to its cost efficient level.

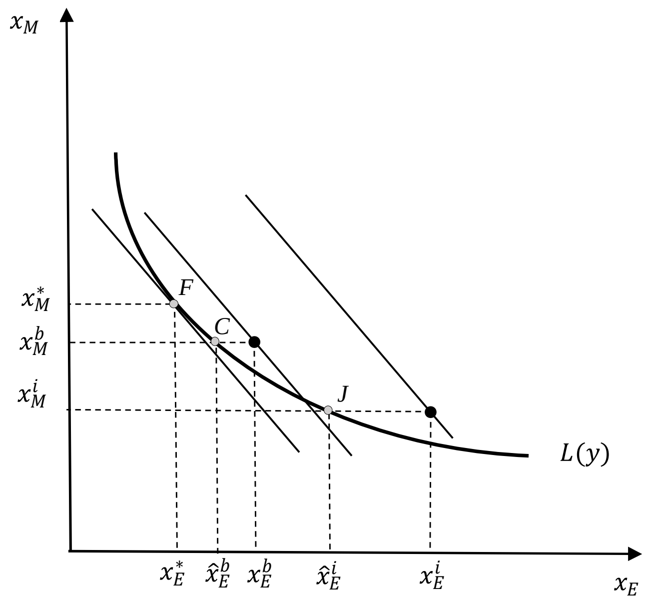
Figure 3 illustrates the cost efficiency decomposition by depicting the simplified case of two firms that produce the same output quantity (*y*) from two inputs: energy (x_E) and materials (x_M). To keep it simple, both firms have the same input prices. Firm *i* consumes x_E^i units of energy and x_M^i of materials, while firm *b* respectively uses x_E^b and x_M^b. The cost efficiency is achieved at point *F*, with optimal input quantities denoted by x_E^* and x_M^*. Both firms are cost and energy inefficient since $x_E^i > x_E^*$ and $x_E^b > x_E^*$, though firm *b* is relatively less inefficient than firm *i*.

Keeping fixed the observed purchased quantity of materials, i.e. by holding the current degree of outsourcing, firm *i* could reduce its costs by producing at isoquant point *J* with energy consumption $\hat{x}_E^i$. Likewise, firm *b* could reduce its excessive consumption of energy up to $\hat{x}_E^b$ at isoquant point C. Therefore, the energy efficiency effect in (5) is measured by the ratio $\frac{x_E^i/\hat{x}_E^i}{x_E^b/\hat{x}_E^b}$.

Figure 3 also reveals that both firms can further reduce their costs if all inputs including materials are adjusted to the cost-efficient point *F*. Specifically, both firms should increase the purchase of intermediate inputs (which typically requires capital and labor adjustments): firm *i* could reduce its energy costs by $w_E\left(\hat{x}_E^i - x_E^*\right)$ and firm *b* by $w_E\left(\hat{x}_E^b - x_E^*\right)$. Consequently, the vertical integration effect reflects the impact on energy costs due to the use of a non-optimal level of outsourcing, and is measured as

$$\frac{w_E^i \hat{x}_E^i \Big/ w_E^i x_E^{i*}}{w_E^b \hat{x}_E^b \Big/ w_E^b x_E^{b*}}$$

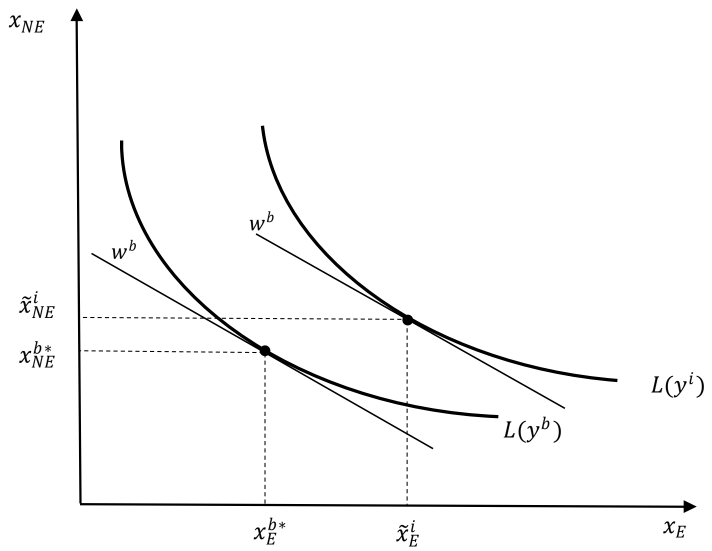
Figure 3. The decomposition of the cost efficiency effect



The third component in (2) is the activity effect. This compares the optimal unit energy cost of a firm with the optimal unit energy cost of the benchmark firm, measured both at the input price vector of the benchmark firm. Therefore it captures the impact of the difference in the output quantity between the *i* firm and the benchmark firm. Figure 4 depicts two isoquants corresponding to the production of two different output levels $y^b > y^i$, as well as their cost minimizing input combinations given input price vector w^b. Accordingly, the activity effect would be given by

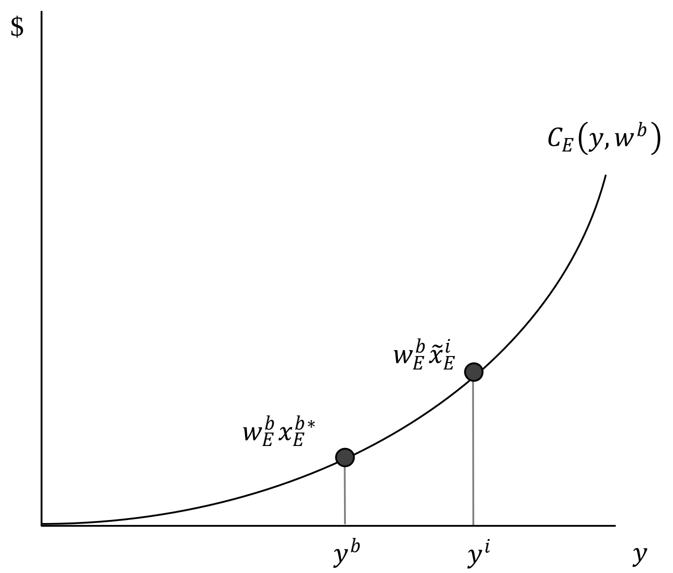
$$\frac{\left(\frac{w_E^b \tilde{x}_E^i}{y^i}\right)}{\left(\frac{w_E^b x_E^{b*}}{y^b}\right)}$$

Figure 4. The activity effect



In the multiple output case the activity effect accounts for differences in the scale and output mix between the two firms. In a single output setting, the activity effect exclusively measures the impact of firms' scale differential on energy costs. Figure 5 makes clearer this point, illustrating a case were the presence of diseconomies of scale in the energy use causes an increase in unit energy cost. Therefore firm *i* in Figure 5 produces a volume of output (y^i) that requires more energy per unit of product than the output quantity produced by the benchmark firm (y^b), i.e. $\frac{w_E^b \tilde{x}_E^i}{y^i} > \frac{w_E^b x_E^{b*}}{y^b}$. In this case, the higher unit energy cost of firm i relative to firm b would be partially explained by its comparatively larger production scale.

Figure 5. The activity effect: the cost function.



Finally, we note that the cross-sectional setting considered we have considered one single technology. That is, we have not considered the possibility that producers can have different technologies in a given year. In principle this can be possible, and therefore it could be possible to identify an additional component to measure the impact of differences in technology between producers on the energy cost gap. However, as Grifell-Tatjé and Lovell (2000) note, as a practical matter it is not possible to construct different cost frontiers for different producers in a given year, since there is only one observation on each producer in a given year.

3. Implementing the energy cost gap decomposition

In the decomposition formulated above the cost efficient energy quantities are not directly observed and must be estimated from the observed data and technology. Technology is also unobserved, so it must be estimated too. We use the linear programming techniques described in Färe et al (1985) to do so.

Using standard notation, we assume that there are J producers who transform a set of inputs $x \in \mathbb{R}_+^n$ into outputs $y \in \mathbb{R}_+^m$. The set of all input-output vectors that are feasible is called the production set (T), which is defined as

$$T = \{(x, y) \in \mathbb{R}_+^{n+m} : x \text{ can produce } y\} \quad (4)$$

We consider a piecewise linear technology constructed from observed data defined by the production set as:

$$T = \Big\{(x, y) : y_m \le \sum_{j=1}^{J} \lambda_j y_m^j, \quad m = 1, \dots, M, \\ \sum_{j=1}^{J} \lambda_j x_n^j \le x_n, \quad n = 1, \dots, N, \\ \lambda_j \ge 0, \\ \sum_{j=1}^{J} \lambda_j = 1, \quad j = 1, \dots, J\Big\} \quad (5)$$

The production technology satisfies monotonicity and convexity, and allows for variable returns to scale.

$$\min \sum_{n=1}^{N} w_n^i x_n$$

$$\text{subject to} \quad y_m^i \le \sum_{j=1}^{J} \lambda_j y_m^j$$

$$\sum_{j=1}^{J} \lambda_j x_n^j \le x_n^i \quad (6)$$

$$\sum_{j=1}^{J} \lambda_j = 1$$

$\lambda_j \geq 0$

where the superscript *i* indicates the producer being evaluated and there are *J* producers in the sample. In our application *M* = 1, *N*= 4 and *J* = 87.

By solving the linear programming problem (6) we obtain the cost-minimizing input vector (x^*) and the minimum total cost $C = wx^*$. In our empirical application we assume that each firm employs four inputs: capital (x_K), labor (x_L), energy (x_E) and intermediate inputs (x_M). Therefore, from (5) we obtain the cost minimizing input vector $x^* = x_K^*, x_L^*, x_E^*, x_M^*$ for each producer. Hence, $C_E(y^i, w^i)$ in expression (2) is the minimum energy cost that results from multiplying the cost minimizing energy quantity (x_E^*) that results from (6), by the price of energy (w_E).

We consider next the estimation of the energy cost necessary for the calculation of the energy input price effect. This requires the identification of the energy quantity input $\tilde{x}_E$ discussed above, which minimizes the cost of producing output y_i, when all input prices of firm *i* are replaced by the input prices of the benchmark firm. We denote as $\tilde{x}$ the cost minimizing vector in this case and can be obtained as the solution to the following linear programming problem:

$$\min \sum_{n=1}^{N} w_n^b x_n$$

subject to $y_m^i \leq \sum_{j=1}^{J} \lambda_j y_m^j$

$$\sum_{j=1}^{J} \lambda_j x_n^j \leq x_n^i \qquad (7)$$

$$\sum_{j=1}^{J} \lambda_j = 1$$

$$\lambda_j \geq 0$$

By solving (7) we obtain for each firm the input quantities $(\tilde{x}_K, \tilde{x}_L, \tilde{x}_E, \tilde{x}_M)$. Thus, $C(y^i, w^b) = w^b\tilde{x}$ is the minimum cost that results from (7), while energy cost results from multiplying the cost efficient amount of energy by the energy price of the benchmark firm i.e. $C_E(y^i, w^b) = w_E^b\tilde{x}_E$.

To disentangle the energy price effect and the non-energy inputs price effect we need to compute $C_E(y^i, w_E^b, w_{NE}^i)$, that is the minimum energy cost to produce y^i when only the energy input price of each firm is replaced by the energy input price of the benchmark firm. Thus, we have to calculate the energy quantity labeled as x_E' in Figure 2. To that effect we make a partition of the observed input vector into a vector of non-energy inputs x_{NE}, and the energy input x_E, that is $x = \{x_E, x_{NE}\}$, and formulate the following linear programming model:

$$\min \; w_E^b x_E + \sum_{n=1}^{N} w_{nNE}^i x_{nNE}$$

$$\text{subject to} \quad y_m^i \leq \sum_{j=1}^{J} \lambda_j y_m^j$$

$$\sum_{j=1}^{J} \lambda_j x_n^j \leq x_n^i \qquad (8)$$

$$\sum_{j=1}^{J} \lambda_j = 1$$

$$\lambda_j \geq 0$$

From (8) we obtain the minimum energy expenditure that results from multiplying the cost-efficient amount of energy (x_E') by the energy price of the benchmark firm (w_E^b), i.e. $C_E(y^i, w_E^b, w_{NE}^i) = w_E^b x_E'$

Finally, to compute the energy efficiency effect and the vertical integration effect we need to estimate $C_E(y^i, w^i; x_M^i)$ and $C_E(y^b, w^b; x_M^b)$, where the quantity of the intermediate input is kept fixed. We then make a partition of the observed input vector into a vector of variable inputs x_n^v and the fixed inputs x_n^f, that is $x = \{x_n^v, x_n^f\}$ and formulate the following linear programming problem:

$$
\begin{aligned}
& \min \ \sum_{n=1}^{N} w_n^i x_n \\
\text{subject to} \quad & y_m^i \leq \sum_{j=1}^{J} \lambda_j y_m^j \\
& \sum_{j=1}^{J} \lambda_j x_n^{vj} \leq x_n^{vi} \\
& \sum_{j=1}^{J} \lambda_j x_n^{fj} = x_n^{fi} \qquad (9) \\
& \sum_{j=1}^{J} \lambda_j = 1 \\
& \lambda_j \geq 0
\end{aligned}
$$

In our case, the only fixed input is the materials input x_M. Thus, by solving (9) for the firm *i* and the benchmark firm we obtain the cost minimizing input quantities when their respective materials input is held fixed, i.e. $(\hat{x}_K^i, \hat{x}_L^i, \hat{x}_E^i, x_M^i)$ and $(\hat{x}_K^b, \hat{x}_L^b, \hat{x}_E^b, x_M^b)$ Thus, $C_E\left(y^i, w^i; \bar{x}_M^i\right) = w_E^i \hat{x}_E^i$ and $C_E\left(y^b, w^b; \bar{x}_M^b\right) = w_E^b \hat{x}_E^b$

4. An empirical application to Chilean cement companies

We illustrate the decomposition to the benchmarking of energy costs of a sample of Chilean cement firms. We have preserved the maximum degree of homogeneity that the available data allow and the sample only include firms that carry out its activity defined by the four digit level of the International Standard Industrial Classification-ISIC. Specifically our sample comprises of 87 firms operating in the Manufacture of concrete, cement and plaster (ISIC 2695). Data were drawn from the 2011 National Industrial Survey of the National Institute of Statistics of Chile.

We use the gross value of production as the output measure for each company. Firms obtain the output from the utilization of four inputs: Capital, Labor, Energy and Materials. Data on Labor and Materials are readily available from the Industrial Companies Survey, conducted by the National Statistics Institute. Thus, labor quantity is measured by the number of worked hours, while Materials include the purchases of intermediate inputs and services consumed in the production process (excluding energy consumption) measured in monetary units. Labor price is calculated as the ratio of the total remuneration of workers by the number of hours worked. Thus, we obtain the average cost per hour worked in each firm. We assume that all firms have the same price for the input of materials and therefore we assign a unitary price. The quantity of capital is measured by the value of the fixed capital at the end of the year. Capital costs are the sum of depreciation, financial expenses and dividends. The price of capital is computed as the ratio of capital costs and the quantity of capital.

Regarding the energy input, the National Industrial Survey provides the energy costs and the quantities consumed of the different types of energy that each firm may use such as electricity, coal, coke, oil, fuel or gas. Energy quantities are measured in different units (e.g. kilograms, cubic meters, kilowatts hour). Therefore have we converted the different units into tons of oil equivalent (toes). Table A1 in the appendix displays the densities and calorific values of the different types of energies used as conversion factors. The energy price is then calculated by dividing the energy expenditure by the energy quantity, and therefore expressed in $ per toe.

Table 1 provides a summary of the data. We have ordered the 87 firms from lowest to highest output and have calculated the mean and standard deviation for each quarter of the sample. Thus, Q1 refers to the 25 percent of the observations that are smaller than the first quartile of the output distribution, Q2 is the 25 percent of the observations greater than the first quartile and smaller than the median output, Q3 is the 25 percent of the observations that are above the median and smaller than the third quartile, and Q4 includes 25 percent of the observations in the dataset that are greater than the third quartile. For each size range Table 1 shows the mean standard deviation of the variables. Last columns shows the mean values for the entire sample. These are the data corresponding to the average firm we use as a benchmark

Table 1 reveals substantial differences across company sizes. Thus, the average output quantity of the smallest 25 percent of firms (Q1) is about seven times smaller than the average firm, while the average output of the largest firms (Q4) is almost three times greater than that of the average firm. By contrast, there are not big differences in input prices, with fairly similar average prices and dispersion levels between across size intervals.

In principle, any producer can be selected as the benchmark for the others. For instance, one company might be interested in comparing itself against a specific competitor that for some reason is considered particularly close or strategic for that company, while other company may consider more suitable to benchmark itself against a very different competitor.

Further, it is perfectly possible to benchmark every company against the rest of competitors on an individual basis. That is, each firm can perform as many benchmarking as firms are in industry. This is arguably a type of benchmarking analysis that would be of most interest for a particular firm manager, because it would provide a full and detailed picture of that firm's relative energy cost performance. That is not however the objective of our empirical application. We are rather interested in getting a more general perspective. To that effect we look for a benchmark that could be a representative and informative reference for all firms in the industry. Thus we have created a fictitious average competitor. Specifically, we have constructed an average firm with the average sectoral values for output and inputs and included it as an additional observation. Each firm has been therefore benchmarked against this average firm.

Table 1. Data summary

Variable	Q1		Q2		Q3		Q4		Total sector	
	mean	*s.d*	*mean*	*s.d*	*mean*	*s.d*	*mean*	*s.d*	*mean*	*s.d*
Output (y)	522,023	320,710	1,550,733	297,315	2,807,366	516,439	9,125,750	7,924,923	3,705,735	5,375,390
Input quantities										
x_K	152,410	119,039	425,830	260,093	883,203	647,727	3,632,136	3,841,810	1,360,214	2,474,387
x_L	75,315	42,022	199,325	62,758	343,485	138,103	1,016,676	842,910	430,667	580,610
x_E	21	15	48	17	100	33	276	196	117	146
x_M	290,989	202,072	931,356	267,916	1,762,795	399,762	6,522,724	6,194,065	2,528,727	4,093,349
Input prices										
w_K	0.126	0.024	0.115	0.033	0.119	0.031	0.118	0.035	0.120	0.031
w_L	1.271	0.201	1.316	0.214	1.295	0.206	1.282	0.208	1.296	0.204
w_E	640	60	656	90	613	50	633	63	636	67
w_M	1.000	0.000	1.000	0.000	1.000	0.000	1.000	0.000	1.000	0.000

Output, Capital and Materials are in thousands of Chilean pesos.

Labor is in number of hours.

Energy is in toes.

Prices are in thousands of Chilean pesos per unit of input.

5. Results

Table 2 reports the mean results of the *energy cost gap* and its five components, by firm size intervals discussed above. We note that these are the mean values of the individual results obtained for firms within each group. Thus, first column in Table 2 shows the average unit *energy cost gap*. First value of the column indicates that the smallest firms in sample (i.e. those within the first quarter Q1) have on average a unit energy cost that is 20.5% higher than that of the average firm. Firms of Q2 have the closest unit energy cost to the average firm, slightly above (1.3 percent), while Q3 and Q4 firms respectively show costs that are 9% and 5.4% higher than that of the average firm.

The energy cost gap in the group of smallest companies is caused by the *energy efficiency effect* and the *activity effect*, which are the components showing values greater than one in the first row of Table 2. Particularly, the energy efficiency effect shows a value of 1.158, indicating that the energy use is on average more inefficient than the mean company, which contributes to increase its unit energy cost above the average firm by 15.8%. The value of the *activity effect* is shown in the last column (1.137), indicating that the small scale of production of firms within this group would cause on average a 13.7% higher unit energy costs than the benchmark average firm. This results suggest the presence of significant scale economies in the use of energy. This is reinforced by the values less than one shown in the other size ranges for the activity effect. Thus, the unit energy cost of the biggest firms (i.e. those included in Q4) is 7.5 percent lower because of their large scale in relation to the mean scale.

The other three drivers of the energy cost gap of the group of smaller companies (vertical integration effect and energy and non-energy inputs price effects) take values less than one, as shown in the first row of Table 2, therefore indicating that these effects contribute to lower the unit energy costs in comparison to the average firm. The impact of the energy price differential between Q1 firms and the average firm is fairly modest (0.7%), while the cost variance due to discrepancies in non-energy input prices is virtually negligible (less than 0.1 percent). The value of the vertical integration effect (0.960) indicates that on average, the degree of vertical (dis)integration of Q1 firms helps them to cut their unit energy cost by 4% in relation to the average firm.

The elements corresponding to the largest Q4 firms are shown in the fourth row. First, the *energy efficiency effect* is the highest (1.198). That is, firms in this group are significantly more inefficient than the average firm, which lead them to have a 19.8% higher energy unit cost. Largest firms have therefore a great room for improving the use of energy in their production processes. This effect is partially mitigated by the rest of elements that are less than one in all cases. In addition to the scale effect discussed above, largest firms seem to face a more favorable price structure, allowing them to enjoy lower energy costs than the average.

Table 2. Results of the energy cost decomposition. Mean results by firm size ranges

	Energy cost gap	Energy price effect	Non-energy inputs price effect	Energy efficiency effect	Vertical integration effect	Activity effect
Q1	1.205	0.993	0.999	1.158	0.960	1.137
Q2	1.013	1.020	1.023	1.010	1.031	0.942
Q3	1.090	0.987	1.004	1.115	1.005	0.989
Q4	1.054	0.985	0.988	1.198	0.992	0.925

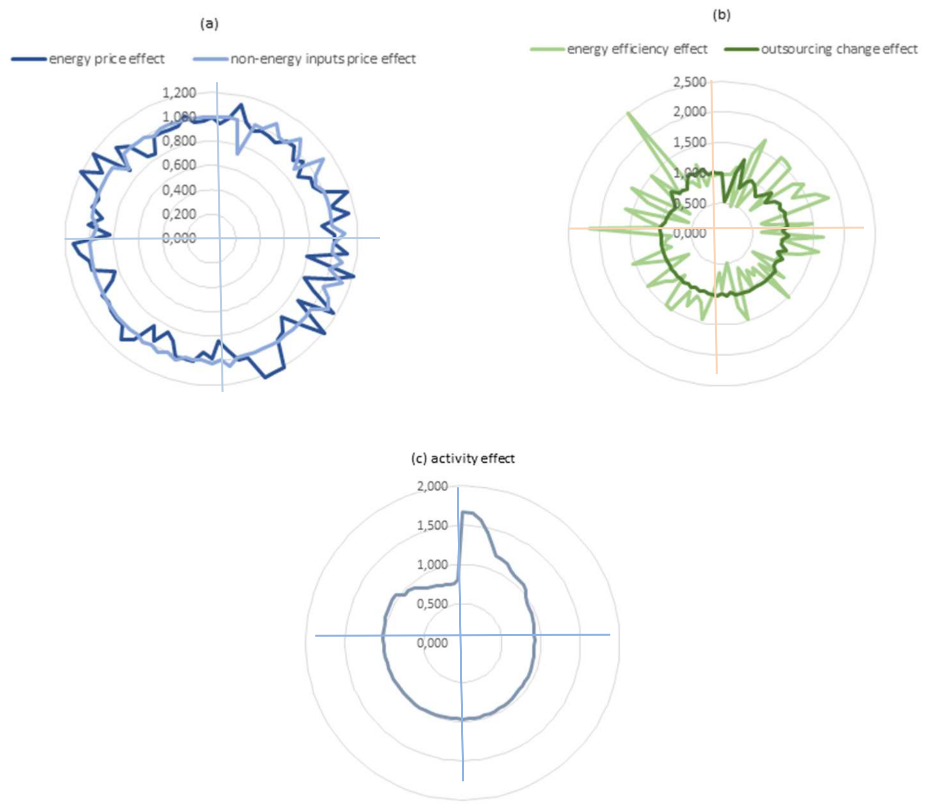
Note: Q1, Q2, Q3 and Q4 respectively denote the first, second, third and fourth 25 percent of firm in the sample ordered from the smallest to largest output size.

Figure 6 depicts the individual results of the five components for all firms, ordered from the smallest to largest. Thus, each quadrant includes the results corresponding to the companies in each size group. That is, first quadrant includes the results of the 25 percent of the observations that are below the first quartile of output, i.e. the smallest firms, while the fourth quadrant includes those of Q4. Panel (a) shows the *energy price effect* and the *non-energy inputs price effect*.

These two effects are quite smooth. Energy prices causes more variation across firms, though in any case goes beyond 20 percent of the cost gap with respect to the benchmark average firm. Panel (b) makes clear that there exist a wide variability in the element of the *energy efficiency effect.* Both below average and above, there are substantial difference between firms in all quadrants. Likewise, the picture allows revealing some extreme inefficient observations. There is much less variation in the outsourcing effect, being more relevant in the first and fourth quadrants.

Panel (c) shows the *activity effect*, in which we can see how that the highest values are concentrated in the smallest firms and the lowest values in the largest firms, being fully consistent with the scale considerations discussed above.

Figure 6. The distribution of the components of the unit energy cost gap



6. Conclusions

In this chapter, we have presented a model for benchmarking the energy cost variance across firms. Particularly, we have develop a Konüs index-based cost frontier approach to the interfirm comparison of unit energy cost and its drivers. The model allows the decomposition of the energy cost gap between two firms, the gap being the difference between the energy cost of a benchmarking producer and the energy costs of a target firm. Then, we have illustrated the implementation and the usefulness of the model to the benchmarking of energy costs of a sample of Chilean cement firms.

From the managerial perspective, the decomposition proposed is useful for assessing a company's energy performance of a company in comparison with firms' direct competitors. Further, it is useful to identify the magnitude and the nature of the drivers of the energy cost discrepancies. Thus, some sources are beyond the full control of the managers (largely input prices), while others are fully manageable. Further, some of them are readily manageable in the short run (e.g. energy efficiency) and others require long-run adjustments (e.g. vertical integration effect, activity effect).

From a policy perspective, the identification of the energy cost drivers and its relevance can be helpful to guide structural reforms and orientate industrial policies. For instance, benchmarking results on the vertical integration and activity effects can have implications for the public support of mergers and acquisitions intended to foster the vertical and horizontal consolidation of the industry. Likewise, the presence of substantial cost gaps due to energy price and energy efficiency effects may lead to public decision makers to consider investments in infrastructures to reduce energy prices or to reduce transport costs (those particularly relevant for the cement industry).

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APPENDIX

Table A1. Densities and calorific values.

	Density tonne/m^3	Calorific value kcal/kg
Petroleum liquid gas	0.550	12,100
Gasoline	0.730	11,200
Diesel	0.840	10,900
Liquefied natural gas (LNG)		9,341*
Electricity		860**
Coal and coke		7,000

Source: Chilean Energy Efficiency Agency
* kcal/m3
** kcal/kwh

Chapter 3.

The increase of energy efficiency and the economy-wide rebound effect: A Computable General Equilibrium analysis for Spain.

1. Introduction

As discussed in the two preceding chapters, in comparison with other countries the Spanish economy traditionally uses a higher amount of energy per unit of generated output, suggesting that there is still much to be done to improve its efficiency in the use of energy. In this sense, Economics for Energy (2011) estimates that technological progress and the application of existing savings policies would achieve by 2030 a reduction of 26% of energy demand in Spain. The implementation of more determined policies in favor of the adoption of the most efficient technologies in the different sectors would entail an additional reduction of 19% on the expected trend scenario for 2030.

This is also the objective of the strategy for the energy savings and energy efficiency promoted by the Spanish government (MITYC, 2007, 2011). These plans are based on the promotion of good consumer practices and technological innovation, which ultimately represents the engine for continuous improvement in energy use and its transformations (Binswanger, 2001). They include estimates of potential energy savings, under alternative scenarios, which could be derived from improved energy efficiency.

Nevertheless, such predicted energy savings are solely based on technical or engineering standards, ignoring the potential changes that may follow in consumers' and producers behavior as a result of the energy efficiency improvements. Specifically, energy saving innovations reduce the cost of providing energy services such as heating, lighting, transport, industrial power, etc. This reduction in cost may encourage consumers and firms to use more of the service. As a result, energy consumption usually does not decline by as much as the rate of technological progress would imply. The difference between the improvement in energy efficiency and the rate of actual reduction in energy consumption is known as the rebound effect.

However, it is hard to find in the targets established in the energy savings policies any prediction of *rebound effects* that could (partially) offset the potential energy reductions. Less common is still to quantify in which sectors or what types of energy are more likely to produce the desired energy savings effect, or what consequences could result from improved energy efficiency on other variables such as employment, prices or GDP, despite multiple economic benefits that any improvement in energy efficiency is alleged to bring (IEA 2014).

In this chapter we analyse these issues in the Spanish economy through a computable general equilibrium (CGE) model to study the economy-wide effects of an increase of energy efficiency in the Spanish economy. We simulate a number of alternative scenarios in order to estimate the rebound effect across sectors and energy types, as well as the impact on economic growth and employment.

The chapter is organized as follows. Section 2 briefly summarizes the relationship between energy efficiency and the rebound effect. Section 3 presents the CGE model. Section 4 describes the calibration and data. The results are shown in section 5. Section 6 includes a large sensitivity analysis on crucial assumptions. Section 7 summarizes the main conclusions.

2. Energy productivity and energy consumption: the rebound effect

At first sight, it seems natural to expect that an improvement in productivity in the use of energy, an increase in output per unit of energy, should immediately be converted into a reduction in the energy consumption of equal proportion. However, there are several reasons why the potential for energy savings may not correspond to real savings. Improvements in energy efficiency can lead to reductions in energy consumption lower than expected because of rebound effects. In other words, part of the technical or 'engineering' estimate of energy savings could be offset by what it is known as rebound effect.

The rebound effect (*RE*) is defined as the ratio between the actual energy savings (*AES*) obtained from increasing energy efficiency, and the potential energy savings (*PES*). The potential energy savings refers to the engineering effect of introducing a more energy-efficient technology, e.g. an engine that consumes a 10% less energy to produce the same amount of output. Therefore

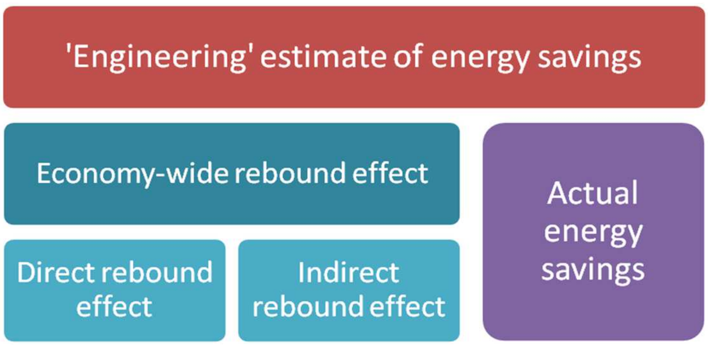
$$RE = \left(1 - \frac{AES}{PES}\right) \times 100 \qquad (\mathbf{1})$$

For instance, if a 10% improvement in vehicle fuel efficiency results in only a 6% drop in fuel use, there is a 40% rebound effect, i.e. $RE = \left(1 - \frac{6}{10}\right) \times 100 = 40$. The 'missing' 4% might have been consumed by driving faster or further than before.

The idea about how the improvement in energy efficiency affects the final quantity of energy consumption, and thereby that the potential energy savings may not match the real savings, was first noted by Jevons (1865) in his book "The coal question". Jevons observed that the introduction of the new efficient steam engine initially decreased coal consumption which led to a drop in the price of coal. This meant that more people could afford to consume coal, but also that coal became economically viable for new uses, which ultimately led to an increase of the quantity of coal consumed. These considerations were further developed by Khazzoom (1980, 1987) and Brookes (1978), leading to Saunders (1992) to state the so-called Khazzoom-Brookes postulate: "energy efficiency improvements that, on the broadest considerations, are economically justified at the microlevel, lead to higher levels of energy consumption at the macrolevel”. Saunders (2009) and Sorrell (2009a) provide an excellent summary of the theoretical underpinnings of the rebound effect and its estimation.

As Turner (2009) explains, the rebound effect is the umbrella term for a variety of economic mechanisms that reduce the energy savings resulting from the improvement of energy efficiency. The origin of the rebound effect is the change in the effective price of energy. That is, if the efficiency of any production factor increases, its price per unit of service (i.e. its effective price or implicit price) is reduced. This triggers a positive response of the demand, both directly (by the producer or consumer whose efficiency has improved), and economy wide through a number of indirect knock-on effects. The strength of this demand is what determines the magnitude of the rebound effect (Turner, 2009). Figure 1 illustrates the different components of the rebound effect.

Figure 1. Components of the Rebound Effect.



Source: Sorrell (2007)

The direct effects have two origins: the substitution effect and the income/ output effect. The substitution effect refers to the incentive to use more energy inputs because their effective price has fallen. In the case of final energy consumers, the substitution effect occurs when, after the introduction of an improvement in energy efficiency, the consumption of the energy service replaces the consumption of other goods and services, maintaining the same level of utility. In the case of producers or companies, the substitution effect occurs when the energy input replaces the use of capital, labor or materials to produce a certain level of output.

The income effect occurs when the increase in consumers' real income resulting from the cheaper energy input is intended to increase the consumption of additional energy services. A similar output effect occurs in the production side, when producers use the cost savings from energy efficiency improvements to increase production, which in turn requires more energy inputs.

In addition to the direct effect on the energy demand of consumers and companies, there is a series of more indirect effects that affect the overall energy demand. Thus, consumers may use their higher income from energy savings to increase the consumption of other goods and services, which in turn require energy for their production and provision. Likewise, firms may increase their production because of the output effect referred to above, which requires increasing consumption of capital, labor and materials, which themselves require energy to provide.

Further sources are the compositional effects, related to changes in the participation of the different sectors in the economy. Thus, given that the relatively energy intensive products benefit more from the fall of the effective prices of the energy, these sectors show a greater relative growth.

Finally, there is also a competitiveness effect, caused by the fall in the prices of commodities that use energy as a factor of production, which increases productivity and stimulates economic growth.

In principle, the rebound effect (RE) in expression (1) above can take any value. The literature establishes five categories of rebound depending on the magnitude of RE, which are shown in Table 1. Thus, if RE is equal to 100 indicates *full rebound*, i.e. the expected efficiency improvement is entirely offset by the rebound type effects discussed above. If RE is equal to zero there is *no rebound*, i.e. all potential energy savings are attained. If RE takes the value between zero and 100 indicates that some potential energy savings are preserved, and therefore it is the case of *partial rebound*. A value of RE greater than 100 indicates that the energy consumption after the efficiency improvement is higher than before. This situation is commonly known as the *backfire effect* or the Jevons paradox (Saunders, 2000, 2009, and Sorrell 2009a). Finally, the case of negative rebound (RE<0) or *super-conservation* is also theoretically feasible, when the actual energy savings are higher than the expected engineering savings.

Table 1. Range of rebound effect (RE)

RE (%)	Types of RE	Implication for energy use
RE < 0	Superconservation/negative rebound	The actual energy savings are higher than expected savings
RE = 0	No rebound / zero rebound	The actual energy savings are equal to expected savings
0 < RE< 100	Partial rebound	The actual energy savings are less than expected savings
RE = 100	Full rebound	The actual energy savings are equal to the increase in usage
RE > 100	Backfire	The actual energy savings are negative because usage increased beyond potential savings

The existence of the rebound effect is uncontroversial. However, debate continues as to the magnitude and impact of the effect in real world situations. There are many empirical studies that estimate the rebound effect in specific sectors. Most of them focus on the analysis of the direct effects, either through experimental or econometric methods. Greening et al. (2000), Sorrell et al. (2009) and Chavravarty et al. (2013) provide comprehensive reviews of this literature, which reveal a wide range of rebound values across sectors and countries. For instance, rebound effects ranging from 15% to 58% have been found in the domestic sector as a result of improved energy efficiency in heating, refrigeration, household appliances and lighting services in develooped countries. Freire-González (2010) estimates a rebound effect of between 35% and 49% in the case of household consumption in Catalonia. In the transport sector, Chavravarty et al (2013) review various studies showing estimates of rebound effects between 30-80%. Rebound effect estimates in manufacturing ranges between 14% and 66% for the United States (e.g. Saunders 2013), 15% -27% in the United Kingdom (Barker et al, 2007), and 43% -96% in the case of India's energy-intensive industries (Sathaye et al, 1999).

Estimates of the magnitude of the rebound effects for the whole economy, or economy-wide rebound effects, are much scarcer, and require computable general equilibrium (CGE) modelling (Greening et al., 2000, Sorrell, 2007; Wei, 2010). Table 2 summarizes the available empirical evidence based on CGE models. The magnitude of the rebound estimates vary substantially among studies, largely due to the diverse structures and size of the economy under analysis, as well as the different assumptions included in the models. Nevertheless, all studies obtain significant rebound effects, usually greater than 50%, and in some cases providing evidence of backfire effects.

Table 2. Evidence for economy-wide rebound effects

Authors	Country	Simulated energy efficiency improvements	Rebound estimates
Semboja (1994)	Kenia	1% in energy production and oil use	>100% in both cases
Dufournaud et al (1994)	Sudan	efficiency increase in wood stoves by 100–200%	47-77%
Grepperud & Rasmussen (2004)	Norway	100% in six sectors	Small rebound for oil, > 100 for electricity
Vikstrom (2004)	Sweden	15% in non-energy sectors and 12% in energy sectors	50-60%
Washida (2004)	Japan	1% in each sector	35-70%
Hanley et al (2005)	Scotland	5% in each production sector	>100%
Allan et al (2007)	UK	5% in each production sector	30-50%
Turner (2009)	UK	5% in each production sector	23% for electricity 30% for non-electricity
Guerra & Sancho (2010)	Spain	5% in each production sector	87.4-90.8%
Lecca et al (2014)	UK	5% in household sector	67.6%-68.2% in household consumption of energy
Broberg et al (2015)	Sweden	5% in each production sector	40-70%

3. The model

In this section we present a CGE model to analyze the impact of an improvement in efficiency in the use of energy in the Spanish economy. Particularly, we will use this model to quantify the impact of a 5% improvement in energy efficiency in all non-energy productive sectors. We present a simulation that introduces an exogenous improvement without costs of the productivity of the energy-related inputs. A 5% improvement is a common value in the literature (see Table 2) and it reflects an attainable technical progress in the medium run represented in this model.

Specifically, we construct a CGE model (Shoven and Whalley, 1984) that describes an open economy, disaggregated into 27 production sectors, with 27 consumer goods, a representative consumer, the public sector and a simplified rest of the world. It allows performing a general equilibrium comparative static analysis.

Previous research has shown that six CGE model features are important for the resulting estimates of the impact of energy improvements on energy use (Allan et al., 2007). First of all, we explain how we overcome them. (1) Treatment of energy in the production function: we base the nestings on MIT-EPPA, which is backed with econometric estimates (see Paltsev et al., 2005). (2) Sensitivity of results to the elasticities of substitution with energy in production: we perform a deep sensitivity analysis on them in section 6. (3) Capital closure: we perform a sensitivity analysis on different capital closure rules in section 6. (4) Treatment of the labour market: Unlike similar models, this model has the particular feature of including unemployment as a specification derived from the literature of trade unions models, given the high unemployment rate of the Spanish economy. Additionally, we perform the sensitivity analysis of different assumptions on wage flexibility and substitutability in section 6. (5) The role of increased government revenue from increased economic activity: We apply a revenue neutral rule, isolating the role of the public sector in the model. (6) The modelling of the energy efficiency improvement: we apply an *autonomous energy efficiency improvement* (AEEI) at different quantitative levels, to check the robustness of the results.

Next we present a brief description of the model. The basis of the complete system of equations is shown in the appendices.

3.1. Equilibrium conditions

The equilibrium of the economy is given by a vector of prices and allocation of goods and factors that simultaneously solves three sets of equations:

- Zero profit conditions for all sectors.
- Market clearance in goods and capital markets.
- Restrictions on disposable income (which is matched with the expenditure incurred by all agents), an unemployment rule, and the macroeconomic closure of the model.

3.2. Production

The production is based on a nested technology of intermediate inputs, capital and labour. The producers' problem is to maximize profits (or, alternatively, minimize costs, in the dual approach), subject to technological constraints. The technological constraints are nested production functions with special detail in energy inputs and outputs (see equations in Appendix I and Figures in Appendix II; based on Paltsev et al., 2005). The solution to the problem yields the average cost functions, which are used in the zero profit conditions. The demands for factors and intermediate inputs are derived from the application of Shephard's lemma to the cost functions, and then used in the equilibrium market clearance equations of goods and factor markets. Firms operate under constant returns to scale and under a competitive pricing rule.

3.3. Consumption

There is a representative consumer who behaves rationally. The consumer's income level is determined from the endowments of capital and labour, plus exogenous net transfers received from the public sector. The consumers' problem is to choose the optimal consumption basket by maximizing a nested utility function (see Figure in Appendix 1, based on Paltsev et al., 2005) subject to its budget constraint. The preferences are represented by a nested utility function whose arguments are savings, leisure, and (consumption of) goods. The budget constraint includes total factors' income, plus exogenous net transfers received from the public sector, minus exogenous income taxes. The demand functions for savings, leisure and goods are derived from the first order conditions, and they are included in the equilibrium conditions of markets, as well as in the macroeconomic closure for savings.

3.4. Public sector

The public sector plays a dual role in the model: it owns resources and it acquires certain goods. As a resource holder, the income includes income from its capital income, net transfers paid to the representative consumer, net transfers received from the rest of the world, and tax revenues. In turn, taxes consist of social contributions paid by employers and employees, indirect taxes (value added tax, other net taxes on products, net taxes on production) and income taxes. All taxes are modelled as *ad valorem* effective rates calibrated from the initial data, except for income taxes that are taken as an exogenous transfer to the public sector.

3.5. Foreign sector

The model incorporates the small open economy assumption. That is, the economy would face a perfectly elastic export supply function. Furthermore it uses a CET function between domestic and foreign sales. With respect to imports, we assume that goods are differentiated according to their origin (i.e., domestic or foreign), following the Armington assumption. This allows for intra-industry trade (Armington, 1969). The foreign sector is closed by assuming that the difference between revenues and payments from the rest of the world is exogenous. This restriction would prevent, for example, the coexistence of a permanent increase in exports without changes in imports providing an unlikely scenario because it would mean capital outflows without any limit.

3.6. Factor markets

There are two primary inputs: capital and labour. With regard to capital, both the representative consumer and the public sector own fixed endowments. Capital rent adjusts to balance the domestic market of that factor. Capital is immobile internationally but there is perfect mobility among domestic sectors.

The sole owner of labour is the representative consumer. We assume the possibility of unemployment and leisure, so labour supply is elastic. We further assume that workers have some degree of market power and their wage demands are related to the level of unemployment in the economy. To do this we model the labour market including the equation (see Kehoe et al., 1995):

$$\mathrm{w} = \left(\frac{1-u}{1-\bar{\mathrm{u}}}\right)^{1/\beta}$$

where w is the real wage, u is the unemployment rate, $\bar{u}$ is the unemployment rate in the benchmark year, and β is a parameter that measures the flexibility of real wages with respect to the unemployment rate. Thus, when β approaches infinity, the real wage is close to its value in the benchmark year (which is 1, after the calibration process described in Section 4). This is the case of rigid wages, where real wage does not vary when the unemployment rate does. If β approaches zero, the unemployment rate is close to the benchmark year, indicating the flexibility of wages. Other intermediate values of β show the greater or lesser degrees of sensitivity of real wages to changes in the unemployment rate. As in the case of capital, labour is assumed immobile at international level but perfectly mobile across sectors.

3.7. Macroeconomic closure for investment and savings.

The total investment is distributed by sector using a fixed coefficient Leontief structure (Dervis et al., 1981). Note that, in our static framework, investment affects the economy as a component of final demand. The model incorporates a macroeconomic closure equation by which equates investment and savings (private, public and external).

Finally, the model is solved by the method of Rutherford (1999), which sets out the general equilibrium models as mixed complementarity problems (Mathiesen, 1985) and it is implemented in the empirical application using the GAMS / MPSGE program (for a presentation, see Hosoe et al., 2010).

4. Calibration, data and simulations

The model is calibrated using data for the Spanish economy. The calibration of benchmark equilibrium is represented by the National Accounts data, and is reflected in the Social Accounting Matrix (SAM) with a set of elasticities taken from the available empirical evidence. A detailed explanation of the calibration technique used can be found, e.g., in Mansur and Whalley (1984) or in Dawkins et al. (2001).

The SAM includes a transformation of the 2005 Symmetric Table for the Input-Output Framework of the Spanish economy (INE, 2011). The starting point is in the 73 sector Input-Output framework for the Spanish economy in 2005. They are grouped in 27 sectors, achieving the highest possible level of disaggregation in the energy sectors and in energy intensive sectors. The SAM is accomplished with data from the National Accounts through the Accounts of institutional sectors. The economic activities comprising the 27 sectors are listed in Table 3.

It has been published a more recent Symmetric Input-Output Table, but the deep crisis in Spain in 2010 (e.g., unemployment rate was 19.86%, while it was 9.15% in 2005) was a critical point for this selection. Many adjustments were taken place at macroeconomic and microeconomic level in the Spanish economy. Those arguments have been considered relevant to discard the 2010 Input-Output Table.

Moreover, as the elasticities play a key role in the model, a sensitivity analysis on the values selected in order to compare their possible effect on the results of the simulations is displayed in section 6.

The elasticity values applied for calibration are taken from Paltsey et al. (2005). They develop econometrics estimates on the production side for the CGE MIT-EPPA model for the USA economy. Therefore, it is assumed that Spanish nested production function can be proxied with the USA nestings (see Appendix II). Those values are:

• Elasticities of substitution in the utility function:

- Between consumption and savings (σ_{CA}): 1

- Between final consumption and leisure (σ_{CO}): 1

- Among final consumption goods (σ_{BC}): 1

• Elasticities of substitution associated to production:

- Between intermediate inputs and value added (σ_{I}): 0
- Between labour and capital (σ_{LK}): values for sectors ranging from 0.20 to 1.68
- Armington elasticities (between domestic and imported goods): the values for the sectors are between 0.90 and 4.05
- CET elasticities (between national and foreign sales): the values of the sectors are between 0.70 and 3.90

Regarding the sources, the values of σ_{LK} and Armington elasticities σ_{A} are from Narayanan and Walmsley (2008), the elasticities of transformation by De

Melo and Tarr (1992), and σ_{CO} is consistent with the empirical literature review conducted by Ballard and Kang (2003). The rest of the values used are those conventional in the literature.

Table 3. The industrial disaggregation and NACE codes

Sector's name	**NACE-93**
Agriculture	01,02,03
Mining of coal	10
Extraction of crude petroleum and gas	11,12
Mining & quarrying	13,14
Refined oil products	23
Electricity	401
Gas	402-403
Water	41
Food	15,16
Textile	17,18
Chemical	24
Rubber and plastic	25
Cement	265
Glass	261
Ceramic products	262-264
Other non-metallic minera	266-268
Manuf. of basic metals	27
Metal products	28
Equipment	29-33
Transport equipment	34,35
Paper	21,22
Other manufacturing industries	20,36,37
Construction	45
Wholesale and retail trade	50-52, 55.1-55.5
Transport	60-63
Market services	64-67,70-74, 80p,85p,90p,91p,92p,93
Non-market services	75,80p,85p,90p,91p,92p
Households	95

The simulation consists in an energy augmenting technical change leading to a reduction in the use of four energy intermediate inputs per unit of output produced in all sectors, and also in the representative agent's final consumption. The four intermediate inputs are those corresponding to Coal, Refining, Electricity and Gas (see Table 3). The increase improves the technology available to the producers and alters their production functions, and improves the consumers' energy efficiency and also alters the welfare function. We consider three simulation scenarios:

(i) Scenario 1. We simulate 5% increase in energy efficiency in all non-energy productive sectors.

(ii) Scenario 2. We simulate a 5% increase in energy efficiency in the final consumption (households).

(iii) Scenario 3. We simulate a 5% increase in energy efficiency in all productive sectors.

5. Results

Tables 4 to 6 provide numerical results for the three scenarios considered. Each table displays the percentage change in some variables at sectoral level: consumption of energy intermediate inputs (Coal, Oil Refining, Electricity and Gas); labour and capital inputs employed; output; real price (with respect to the numeraire, namely the CPI in this model) and final consumption. Table 7 shows the rebound effects estimated through equation (1) by energy type under the three alternative scenarios referred to above, while Table 8 reports key macroeconomic variables. The macroeconomic variables analyzed are GDP, welfare, employment, unemployment rate, and real rents of labor and capital.

Table 4 shows the sectoral changes in the use of intermediate energy inputs, final consumption, output and employment under simulation Scenario 1, i.e. after a 5% increase in energy efficiency in all non-energy productive sectors. The results are reported as percentage changes from the base year values (2005).

The last row of Table 4 shows the total variation that would occur in the consumption of the different energies. As might be expected, there is a reduction in the amount consumed of all energy inputs. However, the reduction is lower than the 5% improvement in energy efficiency we have considered. Thus, electricity would be reduced by 2.34%, the consumption of gas by 2.01%, oil refining products by 1.90%, and the demand of coal would fall by 1.76%. Therefore, our results show different magnitude of the rebound effect according to the type of energy: 53.2% for electricity, 59.7% for gas, 61.9% for petroleum products, and 64.8% for coal, as reported in Table 7.

Table 4 also reveals the existence of significant differences between sectors in terms of the magnitude of the impact of improving energy efficiency on final energy consumption, and ultimately the rebound effect. In general, in service sectors, trade, transport, extractive industries and agriculture, where energy consumption is smaller, the lower are the rebound effects. The largest rebound effect occurs in several sectors that are energy intensive, such as chemical industry, ceramics, energy sectors and construction.

Likewise, it becomes clear the different effect that occurs in the use of the energies as intermediate inputs and as final consumption. Thus, there is an increase in the consumption of all energies by private final consumption. Specifically, the 'Final Consumption' column shows an increase in households demand for electricity (0.56%), gas (0.64%), refining products (0.69%) and coal (0.68%). The improvement of labor and capital rents (0.30% and 0.44% respectively) leads to a direct increase in final energy consumption. But this income effect also generates an increase in consumption of the rest of the goods and services by households, as shown by the positive values in the column 'Final Consumption' in Table 4. This reflects the impact of the indirect effect of the increase in the amount of energy needed to produce these goods, while highlighting the relevance of the general equilibrium model to estimate these effects.

As shown in Table 8, total employment grows by 0.45%, but sectoral changes are diverse. Employment increases in all productive sectors, except in the agriculture (-0.27%) and the energy sectors: Coal (-1.93%), Electricity (-1.46%), Gas (-1.01%) and Refining (-0.94%). The largest percentage increase in employment is attained in Oil extraction (1.31%) and Chemical (1.25%). This effect can be exacerbated with the capital fixed-endowment assumption. The model also uses the assumption of free mobility of labor and capital across sectors, but not internationally. If capital use is going to increase in a sector, it must decrease in other sector or sectors. This restriction is less rigid to labor, given the existence of unemployment and leisure. This case is further discussed in section 6.

With respect to changes in the output, these are largely determined by the use of factors. Thus it is found that the evolution of the physical output is highly correlated with the use of the productive factors. Furthermore, in relation to these two factors, in Table 8 it is shown the relative increase in capital rent relative to wages, and Table 4 confirms that this leads to a further decline (or smaller increase) in use of capital relative to labor for each sector.

Changes in real prices are measured relative to a CPI. Therefore, there will be a series of sectorial prices that are below the price level of the index, while for other sectors the change in prices is above the weighted average. The fourth column in Table 4 shows that sectoral prices descend in most productive sectors, with the exception of the price increased in Agriculture (0.13%), Market services (0.11%), Electricity (0.09%) and Trade (0.03%).

These results for Scenario 1 are not easily comparable with other results in the rebound effect literature. As showed in Table 2, there are no studies that applied a 5% improvement on energy efficiency to a subset of sectors. Scenario 2 and 3 can be compared to some of those research studies, as it is done below.

To further explore the rebound effect in the households sector, we assume in Scenario 2 that efficiency improves only in the energy use by households. Thus, we model a 5% increase in the final use of energy for the representative consumer. Table 5 shows the results of some key variables for each sector. In this case the total household energy consumption would be reduced by 3.67%, or 3.68% (depending on the energy) indicating a rebound effect of 26.5% and 26.6%, reported in Table 7. This rebound effect is lower than the one showed by Lecca et al. (2014). This difference can be due to the different welfare function used (it has more nestings in our case) and, of course, the different country analyzed (UK vs Spain). As expected, Table 4 shows that the switch in household expenditure away from spending on energy towards other types of consumption has a small impact on the macroeconomic variables, displayed in Table 8, as in Lecca et al. (2014).

Scenario 3 covers the improvement of energy efficiency for all sectors. Except in the energy sectors and in Agriculture, the expansion of the economy generates additional final demand energy use. Note that despite the expansionary effect of the measure at aggregate level, there is a reduction in the quantity of energy consumed in the economy. This expansion, in general, decreases the rebound effect, as Table 7 displays.

A comparison of the scenarios according to the results from Table 8, shows that the efficiency improvement logically leads to an increase in the overall welfare of the economy (excluding the public sector), measured by an index of equivalent variations. The principal source of those welfare gains comes from primary factor markets, labour and capital. In scenarios 1 and 3 there are gains in the size of labour employed and in both factor rents. Full employment is assumed in the case of capital factor, while involuntary unemployment represents a relevant characteristic of the Spanish labour market. This allows a simultaneous increase in employment and a decrease of unemployment derived from productivity improvements, as scenarios 1 and 3 have.

The improvement in the real factors income, along with higher employment, are the generators of welfare growth in scenarios 1 and 3. Both workers and capital owners would improve their unitary real incomes. However, the improvement in capital rents exceeds quantitatively the improvement in real wages, suggesting that improvements in energy efficiency would have a redistributive effect in relative terms. Several forces generate this lower relative improvement of wage. Labour supply is elastic and there is the possibility of unemployment, while the endowment of capital is fixed and it is fully employed, which implies a vertical supply function of capital. An economic expansion, therefore, would lead to a further increase of capital rent in relation to the increase in labour wage. The evolution of capital rent is particularly favourable in Scenario 3 that involve efficiency improvements in energy sectors. This is consistent with the fact that the main energy sectors (Electricity, Refining, Gas) are capital intensive, so their rebounds effects stimulates especially the capital demand over labor demand.

Table 4. Sectoral changes under Scenario 1.

	EMPLOYMENT	CAPITAL	OUTPUT	PRICE	FINAL CONSUMPTION	COAL	REFINING	ELECTRICITY	GAS
Agriculture	-0.27	-0.33	-0.13	0.13	0.53	-3.40	-3.37	-3.53	-3.48
Coal	-1.93	-2.04	-1.94	-0.19	0.68	-1.84		-1.94	-1.94
Oil extraction	1.31	1.16	1.29	-0.34			-3.77	-3.77	-3.77
EXTMIN	0.47	0.37	0.87	-0.59	0.98	-2.44	-2.42	-2.58	-2.52
Oil refining	-0.94	-1.63	-1.34	-0.22	0.69	-1.27	-1.24	-1.40	-1.35
Electricity	-1.46	-2.01	-1.81	0.09	0.56	-1.65	-1.64	-1.81	-1.74
Gas	-1.01	-1.81	-1.60	-0.11	0.64	-1.60		-1.60	-1.60
Water	0.53	-0.06	0.51	-0.19	0.73		-2.00	-2.16	
Food	0.31	-0.08	0.35	-0.03	0.64		-2.14	-2.32	-2.24
Textile	0.25	-0.19	0.32	-0.18	0.73		-2.16	-2.35	-2.26
Chemical	1.25	0.79	1.83	-0.72	0.87	-1.30	-1.27	-1.43	-1.38
Rubber&plastic	0.48	0.00	0.67	-0.40	0.87		-1.97	-2.15	-2.08
Cement	0.60	-0.11	0.55	-0.42	0.88		-2.10	-2.26	-2.21
Glass	0.56	-0.08	0.68	-0.43	0.88		-1.95	-2.14	-2.05
CERAM	0.55	0.02	0.77	-0.48	0.92		-1.89	-2.10	-2.00
MINER	0.37	-0.11	0.51	-0.39	0.86		-2.12	-2.29	-2.23
Basic metals	0.34	-0.13	0.61	-0.45		-2.21	-2.18	-2.35	-2.28
METAL	0.33	-0.11	0.35	-0.23	0.76		-2.10	-2.28	-2.21
Equipment	0.20	-0.25	0.21	-0.21	0.75	-2.27	-2.24	-2.42	-2.35
Transport equipment	0.29	-0.18	0.31	-0.21	0.75		-2.16	-2.35	-2.27
Paper	0.31	-0.12	0.36	-0.18	0.73		-2.12	-2.32	-2.22
Wood	0.38	-0.06	0.39	-0.16	0.72		-2.07	-2.23	-2.17
Construction	0.69	0.08	0.48	-0.02	0.63		-1.87	-2.02	
Trade	0.72	0.14	0.52	0.03	0.58		-2.37	-2.54	-2.48
Transportation	0.56	-0.04	0.65	-0.55	0.85	-2.50	-2.47	-2.70	-2.57
Market services	0.60	0.17	0.40	0.11	0.50	-2.41	-2.38	-2.59	-2.49
Non-market services	0.05	-0.39	0.07	-0.05	0.07		-2.82	-2.99	-2.92
TOTAL Energies						*-1.76*	*-1.90*	*-2.34*	*-2.01*

Table 5. Sectoral changes under Scenario 2.

	EMPLOYMENT	CAPITAL	OUTPUT	PRICE	FINAL CONSUMPTION	COAL	REFINING	ELECTRICITY	GAS
Agriculture	0,03	0,03	0,03	0,00	0,10	0,01	0,02	0,01	0,02
Coal	-0,79	-0,78	-0,79	-0,01	-3,68	-0,39		-0,39	-0,39
Oil extraction	-1,30	-1,30	-1,30	-0,03			-0,65	-0,65	-0,65
EXTMIN	-0,08	-0,07	-0,07	-0,01	0,10	-0,04	-0,03	-0,04	-0,03
Oil refining	-1,24	-1,21	-1,21	-0,02	-3,67	-0,61	-0,60	-0,61	-0,60
Electricity	-0,89	-0,86	-0,86	-0,01	-3,68	-0,43	-0,43	-0,43	-0,43
Gas	-0,99	-0,96	-0,96	-0,02	-3,67	-0,48		-0,48	-0,48
Water	0,01	0,04	0,02	0,00	0,10		0,01	0,01	
Food	0,05	0,08	0,06	0,00	0,10		0,04	0,03	0,03
Textile	-0,01	0,02	-0,01	0,00	0,10		0,00	0,00	0,00
Chemical	-0,08	-0,05	-0,07	0,00	0,06	-0,03	-0,03	-0,03	-0,03
Rubber&plastic	-0,09	-0,06	-0,08	0,00	0,10		-0,04	-0,04	-0,04
Cement	-0,05	-0,02	-0,03	0,00	0,10		-0,01	-0,01	-0,01
Glass	-0,06	-0,03	-0,05	0,00	0,10		-0,02	-0,02	-0,02
CERAM	-0,07	-0,04	-0,07	0,02	0,09		-0,03	-0,03	-0,03
MINER	-0,03	0,00	-0,02	0,00	0,10		-0,01	-0,01	-0,01
Basic metals	-0,13	-0,10	-0,11	0,00		-0,06	-0,05	-0,06	-0,05
METAL	-0,08	-0,05	-0,07	0,00	0,10		-0,03	-0,03	-0,03
Equipment	-0,10	-0,07	-0,09	-0,01	0,11	-0,04	-0,04	-0,04	-0,04
Transport equipment	-0,09	-0,06	-0,08	0,01	0,10		-0,03	-0,04	-0,03
Paper	-0,02	0,01	-0,01	0,00	0,10		0,00	0,00	0,00
Wood	-0,04	-0,01	-0,03	0,00	0,10		-0,01	-0,01	-0,01
Construction	-0,02	0,02	-0,01	0,00	0,10		0,00	0,00	
Trade	0,05	0,09	0,07	0,00	0,10		0,04	0,03	0,04
Transportation	-0,04	0,00	-0,02	0,00	0,05	-0,01	-0,01	-0,01	-0,01
Market services	0,01	0,04	0,03	0,00	0,10	0,01	0,02	0,02	0,02
Non-market services	0,01	0,04	0,01	0,01	0,01		0,01	0,01	0,01
TOTAL Energies	-0,01	0,00				*-0,35*	*-0,20*	*-0,09*	*-0,22*

Table 6. Sectoral changes under Scenario 3.

	EMPLOYMENT	CAPITAL	OUTPUT	PRICE	FINAL CONSUMPTION	COAL	REFINING	ELECTRICITY	GAS
Agriculture	-0,38	-0,48	-0,20	0,26	0,79	-3,93	-3,05	-2,56	-4,33
Coal	-3,62	-3,79	-3,63	-0,57	0,88	-5,58		-8,45	-8,45
Oil extraction	2,37	2,15	2,35	-0,43			-2,77	-2,77	-2,77
EXTMIN	0,60	0,45	1,13	-0,75	1,43	-2,62	-1,72	-1,30	-3,03
Oil refining	-1,21	-2,24	-0,39	-1,47	1,25	-5,06	-4,19	-3,67	-5,46
Electricity	-1,80	-2,62	-0,94	-2,55	1,70	-4,78	-4,52	-4,11	-5,55
Gas	-2,34	-3,51	-3,20	-0,15	0,71	-8,04		-8,04	-8,04
Water	0,82	-0,06	0,78	-0,22	1,10		-1,13	-0,59	
Food	0,47	-0,13	0,50	0,02	0,94		-0,97	-0,87	-2,28
Textile	0,35	-0,33	0,42	-0,19	1,07		-0,97	-0,94	-2,29
Chemical	1,52	0,82	2,22	-0,86	1,17	-1,24	-0,34	0,13	-1,66
Rubber&plastic	0,60	-0,11	0,86	-0,49	1,26		-0,95	-0,73	-2,26
Cement	0,88	-0,19	0,79	-0,56	1,31		-1,31	-0,79	-2,61
Glass	0,75	-0,22	0,85	-0,51	1,27		-0,70	-0,69	-2,01
CERAM	0,69	-0,11	0,91	-0,49	1,27		-0,55	-0,66	-1,86
MINER	0,54	-0,19	0,73	-0,50	1,27		-1,23	-0,84	-2,54
Basic metals	0,45	-0,27	0,76	-0,54		-2,05	-1,15	-0,98	-2,46
METAL	0,48	-0,19	0,50	-0,27	1,13		-1,02	-0,83	-2,33
Equipment	0,28	-0,40	0,29	-0,25	1,11	-2,18	-1,28	-1,03	-2,59
Transport equipment	0,37	-0,34	0,39	-0,23	1,10		-1,12	-0,97	-2,43
Paper	0,48	-0,18	0,52	-0,19	1,08		-0,81	-0,86	-2,12
Wood	0,53	-0,14	0,54	-0,18	1,06		-1,18	-0,76	-2,49
Construction	1,02	0,09	0,70	0,02	0,94		-0,97	-0,43	
Trade	1,09	0,21	0,78	0,09	0,88		-1,51	-1,16	-2,82
Transportation	0,84	-0,06	0,90	-0,62	1,18	-2,65	-1,75	-1,32	-3,05
Market services	0,93	0,27	0,61	0,20	0,76	-2,48	-1,59	-1,24	-2,89
Non-market services	0,09	-0,58	0,11	-0,03	0,11		-2,20	-1,83	-3,50
TOTAL Energies	0,67	0,00				*-4,17*	*-2,47*	*-1,79*	*-3,94*

Table 7. Energy Consumption and rebound effect. Alternative scenarios.

	Scenario 1		Scenario 2		Scenario 3		
	Total energy savings (%)	Rebound Effect (%)	**Direct Energy Use (%)**	**Rebound Effect (%)**	**Total energy savings (%)**	**Total energy savings (%)**	Rebound Effect (%)
Coal	-1.76	64.8	-3.68	26.5	-0.345	-4.17	16.5
Oil	-1.90	61.9	-3.67	26.6	-0.203	-2.47	50.5
Electricity	-2.34	53.2	-3.68	26.5	-0.095	-1.79	64.1
Gas	-2.01	59.7	-3.67	26.6	-0.218	-3.94	21.2

Table 8. Macroeconomic variables

	Scenario 1 (5% in all production sectors except energy sectors)	Scenario 2 (5% in final consumption only)	Scenario 3 (5% in all production sectors, inc. energy sectors)
GDP (at factor cost)	0.61	0.000	0.93
Welfare	0.58	0.086	0.86
Employment	0.45	-0.007	0.67
Unemployment rate	-4.44	-0.152	-6.69
Real wage	0.30	0.010	0.45
Real rent of capital	0.44	-0.012	0.68

6. Sensitivity analysis

In order to check the sensitivity of the results we carry out a sensitivity analysis by estimating our base case Scenario 1 under alternative function specifications, and different values of parameters that are likely to be important in determining the magnitude of rebound effects. Table 8 show the results for the main variables under different model assumptions. The benchmark refers to the base case Scenario 1.

First, regarding the treatment of energy in the production function and the sensitivity of results to the elasticities of substitution with energy in production, we check not only the production functions but also the welfare function (which determines the final demand functions). Thus, columns (2) and (3) show the cases of including Leontief and functions (i.e., zero elasticities of substitution), instead the nested CES function already applied. In columns (4) and (5) we report the simulation results with Cobb-Douglas specifications to represent unitary elasticity case, both for production and utility functions, despite Sanders's (2008) arguments about the unsuitability of the Cobb-Douglas form for the analysis of rebound effects in the case of production functions. While the CD specification does not virtually alter the results in comparison to those obtained with the CES case base, interestingly, results shown in column (4) are fully consistent with Sanders's (2008) arguments about Cobb-Douglas resulting in unrealistically high rebound.

The production functions include sectoral constant elasticity of transformation (CET) functions (see equation A7 in Appendix I). They represent firms' capability to sell production to differentiated markets (home and/or abroad). The elasticities of transformation in the CET functions measure the ease to change the targeted market. For example, zero elasticity indicates that firms cannot sell a commodity made for domestic markets in foreign markets, and vice versa (i.e., commodities are perceived by consumers as so differentiated that are in fact treated as different). Conversely, a high elasticity involves commodities that can be equally sold at home and abroad because they are perceived as very similar or even identical.

Regarding the treatment of the labour market, we perform the sensitivity analysis on two different assumptions on wage flexibility: less rigid wages and more rigid wages. Welfare is sensitive to this assumption, with more welfare gains with wage rigidity, giving the logical stronger positive impact on labour and on capital rents. At sectoral level effects are also different, with a more positive impact on output for the same rigid-wages scenario. We also check different levels of substitutability between labour and capital and there is not a relevant sensibility of the results, as shown in columns (7) and (8) in Table 8.

Column (9) shows the results when we change the assumption of perfect mobility of capital across sectors for the specific factor assumption (i.e. capital immobility across sectors). This scenario can be also interpreted as a short-run scenario. At macro level, real gains for capital decrease, but improve for labour. Nevertheless changes with respect to benchmark are tiny. At sectoral level, output changes less in energy sectors, and in a similar amount for the rest.

Table 8. Sensitivity analysis. Scenario 1.

	(1) Base case	(2) Leontief production	(3) Leontief utility	(4) CD production	(5) CD utility	(6) ε=0	(7) $\sigma_{KL}/2$	(8) $\sigma_{KL} \times 2$	(9) K specific
GDP (at factor cost)	0.609	0.512	0.537	0.558	0.650	0.589	0.477	0.798	0.428
Welfare	0.577	0.492	0.548	0.543	0.573	0.560	0.468	0.733	0.364
Employment	0.448	0.352	0.356	0.349	0.514	0.429	0.282	0.686	0.335
Unemployment rate	-4.435	-3.638	-4.347	-3.794	-4.170	-4.276	-3.186	-6.233	-3.135
Real wage	0.298	0.244	0.292	0.255	0.280	0.287	0.214	0.419	0.211
Capital rental real rate	0.441	0.423	0.406	0.490	0.475	0.437	0.459	0.415	0.301
COAL	-1.761	-3.712	-1.878	0.752	-1.742	-1.814	-1.874	-1.597	-2.047
OIL REFINING	-1.904	-3.870	-2.107	0.831	-1.920	-2.018	-2.017	-1.740	-2.007
ELECTRICITY	-2.338	-4.362	-2.419	0.401	-2.317	-2.370	-2.445	-2.184	-1.840
GAS	-2.014	-4.070	-2.131	0.676	-2.013	-2.074	-2.128	-1.849	-1.614

Note: all variables measure percentual changes.
σ_{KL}= elasticity of substitution between capital and labor
K-specific: capital is specific and immobile between sectors
ε is the elasticity of transformation in CET functions

7. Conclusions and discussion

Improving energy efficiency is a key pillar for reducing energy consumption and greenhouse gas emissions. As we have seen, these objectives can be undermined by the existence of the rebound effect. The nature of the rebound effect is known for a long time, it is its magnitude and relevance that is subject to the debate and empirical evaluation.

The literature reviewed in this paper suggests that, in general, it is unlikely to expect rebound effects greater than 100%, which will cancel out and fully compensate for potential energy savings (backfire effect). Likewise, it is also not likely to find zero rebound effects. It is usual to expect that improvements in energy efficiency lead to lower energy consumption in absolute terms, but lower than expected a priori. As we have shown in the Spanish case, in some sectors and economic activities the rebound effect can be very significant, with the consequent smaller reduction of carbon emissions as the main undesirable consequence.

The empirical evidence therefore suggests that it is necessary to recognize and consider the rebound effects in the design and evaluation of the effectiveness of these policies. However, the examples of energy saving policies that consider the rebound effect are very scarce, we only know a few exceptions in the countries around us. The United Kingdom Department of Energy and Climate Change decided to take into account the direct rebound effect in estimating the potential energy savings resulting from the thermal insulation of households. Thus, 15% of the potential savings was estimated as the so-called comfort-taking effect, i.e. the increase in the household temperature with which consumers respond to the financial savings resulting from the improvement in energy efficiency. Likewise, when calculating the results of energy saving measures, the 2014 National Energy Efficiency Action Plan (DCENR, 2014) assumes a high rebound effect of 70% associated with the comfort effect in low-income households. Beyond these specific cases, the rebound effect is usually ignored in the analysis and design of strategies and plans aimed at estimating the potential energy savings that would result from improvements in energy efficiency.

In Spain, the Energy Savings and Energy Efficiency Plan 2011-2020 mentions the possibility that there would have been some rebound effects on energy consumption in homes and public lighting when assessing the energy savings achieved in these sectors attributable to measures included in previous action plans (MITYC, 2011, pp. 71-75). However, these effects are not quantified and are not taken into account in setting energy saving targets for 2020.

If the magnitude of the rebound effect is not recognized, it is difficult to consider the importance of implementing measures to mitigate it. In this sense, there are instruments and intervention policies in different areas: policies that promote changes in consumer behavior, promotion of sustainable lifestyles, fiscal instruments (e.g. energy taxes and emissions), incentives to Eco-technological innovation, non-fiscal measures to increase the effective price of energy services, or the development of new business models. Maxwell et al (2011) reviews the implications, advantages and disadvantages of all these instruments.

Finally, we note that the same forces that trigger the rebound effect are also driving economic growth. Therefore, to the extent that any mitigating measures of the rebound effect act as forces reducing demand, both objectives seem a priori difficult to reconcile. From the point of view of the public decision maker, therefore, the challenge is to design and implement policies aimed at mitigating the rebound effect that are compatible with economic growth.

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APPENDIX I.

A1. Mathematical formulation

As a general rule, the notation in the model is as follows: the endogenous variables are denoted with capital letters, the exogenous variables in capital letters with bar, while the parameters are denoted by lower case Greek letters. There are 27 (*i*, *j* = 1,...,27) production sectors.

The equilibrium of this economy is defined by a vector of prices and an allocation of goods and factors that simultaneously solves three sets of equations:

- Zero profit conditions for all sectors
- Equilibrium of goods and capital markets.
- Restrictions on disposable rent (which must be matched with the expenditure incurred by all agents), unemployment and macroeconomic closure of the model.

These equations are described below.

Production

The base model has constant returns to scale, and a rule of competitive pricing. There is a variety of production functions (see Appendix II). Here we include the case of the production function for all sectors except agriculture and energy (Coal, Refining, Electricity and Gas).

The top nesting level is a Leontief function, the zero profit condition for sector i (*i* = 1,…, 27; i ≠ Energy (coal, refining, electricity, gas) is:

$$PROFIT_i^x = PX_i\left(1 - oip_i^{ll} - oii_i^{ll}\right) - c_{0i}PVAE_i - \sum_{j=1;j\neq energy}^{27} c_{ij}PO_j = 0 \quad (\mathbf{A1})$$

in which, according to its nested structure, the unit cost of composite added value and energy generated by sector i is a CES function:

$$PVAE_i = \frac{1}{\propto_i}\left[a_i^{\sigma_i^{LKE}} PVA^{\left(1-\sigma_i^{LKE}\right)} + (1-a_i)^{\sigma_i^{LKE}} PE_i^{\left(1-\sigma_i^{LKE}\right)}\right]^{\frac{1}{\left(1-\sigma_i^{LKE}\right)}} \qquad (\mathbf{A2})$$

where:

$$PVA_i = \frac{1}{\gamma_i}\left[h_i^{\sigma_i^{LK}}(1+soc_i)^{\left(1-\sigma_i^{LK}\right)} W^{\left(1-\sigma_i^{LK}\right)} + (1-h_i)^{\sigma_i^{LK}} R^{\left(1-\sigma_i^{LK}\right)}\right]^{\frac{1}{\left(1-\sigma_i^{LK}\right)}} \qquad (\mathbf{A3})$$

$$PE_i = \frac{1}{\chi_i}\left[k_i^{\sigma_i^{ener}}\left(\varphi_i PO_{electricity}\right)^{\left(1-\sigma_i^{ener}\right)} + (1-k_i)^{\sigma_i^{ener}} PCOGR_i^{\left(1-\sigma_i^{ener}\right)}\right]^{\frac{1}{\left(1-\sigma_i^{ener}\right)}} \qquad (\mathbf{A4})$$

$$PCOGR_i = \prod_{i=coal,oil,refining,gas} (\varphi_i PO_i)^{\tau_{ener}} \qquad (\mathbf{A5})$$

We assume that domestic producers maximize profits, and choose the optimal combination of domestic production and imports, and domestic sales and exports. This leads to the following zero profit conditions:

$$PROFIT_i^A = PA_i - \left[e_i^{\sigma_i^A} PX_i^{1-\sigma_i^A} + (1-e_i)^{\sigma_i^A} (\overline{PFX}FC)^{1-\sigma_i^A}\right]^{\frac{1}{1-\sigma_i^A}} = 0 \; (i = 1, \ldots, 27) \; (\mathbf{A6})$$

$$PROFIT_i^{CET} = PA_i - \frac{1}{\zeta_i}\left[d_i^{-\varepsilon_i} PO_i^{\varepsilon_i+1} + (1-d_i)^{-\varepsilon_i} (\overline{PFX}FC)^{\varepsilon_i+1}\right]^{\frac{1}{\varepsilon_i+1}} = 0 \; (i = 1, \ldots, 27)(\mathbf{A7})$$

These conditions of zero profits are used to obtain the demand functions derived through the application of Shephard's Lemma of cost functions.

Then we introduce the equations corresponding to the equilibrium in the markets. On the left side are reflected the demands, and on the right side the supplies:

$$X_i\left(-\frac{\partial PROFIT_i^X}{\partial PO_j}\right) = II_{ji}\ (i,j = 1,\dots,27)\ (\mathbf{A8})$$

$$\sum_{i=1}^{27} X_i\left(\frac{\partial PROFIT_i^X}{\partial R}\right) = \overline{K_{RC}} + \overline{K_{SP}}\quad (\mathbf{A9})$$

$$\sum_{i=1}^{27} X_i\left(\frac{\partial PROFIT_i^X}{\partial W}\right) = (\bar{L} - Q_i)(1-U)\quad (\mathbf{A10})$$

$$A_i\left(-\frac{\partial PROFIT_i^A}{\partial PX_i}\right) = X_i\ (i = 1,\dots,27)\ (\mathbf{A11})$$

$$A_i\left(-\frac{\partial PROFIT_i^A}{\partial FC_i}\right) = IMP_i\ (i = 1,\dots,27)\ (\mathbf{A12})$$

$$A_i\left(-\frac{\partial PROFIT_i^{CET}}{\partial PO_i}\right) = O_i\ (i = 1,\dots,27)\ (\mathbf{A13})$$

$$A_i\left(-\frac{\partial PROFIT_i^{CET}}{\partial FC_i}\right) = EXP_i\ (i = 1,\dots,27)\ (\mathbf{A14})$$

$$X_i + IMP_i = O_i + EXP_i (i = 1,\dots,27)\ (\mathbf{A15})$$

$$I_i + \sum_{j=1}^{27} II_{ij} + CFB_i = O_i (i = 1,\dots,27)\ (\mathbf{A16})$$

Consumption

The functions of final demand for goods resulting from the maximization problem of a nested utility function, which represent the preferences of the representative consumer (here we include one of the welfare functions developed in the paper; see Appendix 2):

$$WF = (Q_c)^{1-\tau_{sav}}(Q_{sav})^{\tau_{sav}} \ (\mathbf{A17})$$

subject to budgetary constraints:

$$Y_{RC} = W(\bar{L} - Q_l)(1-U) + R\overline{K_{RC}} + \overline{NTPS} + \overline{NTFS_{RC}} \ (\mathbf{A18})$$

$$Y_{RC} = P_{sav}Q_{sav} + \sum_{i=1}^{27} PO_i\left(1 + oii_i^{CF}\right)CFB_i^{RC} (\mathbf{A19})$$

in which the nesting of the utility function is defined by:

$$Q_c = \left[b^{\sigma^{CL}} Q_{cg}^{1-\sigma^{CL}} + (1-b)^{\sigma^{CL}} Q_l^{1-\sigma^{CL}}\right]^{\frac{1}{1-\sigma^{CL}}} \quad (\mathbf{A20})$$

$$Q_{cg} = \prod_{i=1}^{27}\left(\varphi_i CFB_i^{RC}\right)^{\tau_i} \ (\mathbf{A21})$$

Consumer goods can be purchased by the representative consumer and the public sector:

$$CFB_i = CFB_i^{RC} + CFB_i^{SP} \ \ (i = 1, \ldots, 27) \ \ (\mathbf{A22})$$

The solution of the maximization problem gives the saving demand function, leisure and final demand.

Public sector

Public sector revenue is given by:

$$\overline{Y_{SP}} = R\overline{K_{SP}} + \sum_{i=1}^{27} (SOC_i + OII_i + OIP_i) - \overline{NTPS} + \overline{NTFS}_{SP} \quad (\mathbf{A23})$$

in which tax revenues come from several sources:

$$SOC_i = Wsoc_i X_i \left(-\frac{\partial PROFIT_i^X}{\partial W} \right) \; (i = 1, \dots, 27) \; (\mathbf{A24})$$

$$OII_i = PX_i oii_i^{ll} X_i \left(-\frac{\partial PROFIT_i^X}{\partial PX_i} \right) + PO_i I_i oii_i^{FBC} \; (i = 1, \dots, 27) \; (\mathbf{A25})$$

$$OIP_i = PX_i oip_i^{ll} X_i \left(-\frac{\partial PROFIT_i^X}{\partial PX_i} \right) + PO_i I_i oip_i^{FBC} + PO_i CFB_i^{RC} oip_i^{CF} \; (i = 1, \dots, 27) \; (\mathbf{A26})$$

On the assumption of neutrality in the public sector behavior, the macroeconomic closure rules are:

$$\overline{BALPUB} = \overline{SAVPUB} - \overline{INVPUB} \quad (\mathbf{A27})$$

$$\sum_{i=1}^{27} CFB_i^{SP} = \overline{Y_{SP}} - \overline{SAVPUB} \quad (\mathbf{A28})$$

Investment, savings and foreign sector

The macroeconomic closure of the model implies other restrictions relating to investment and savings in this open economy:

$$\sum_{i=1}^{27} PO_i \left(1 + oip_i^{FBC} + oii_i^{FBC}\right) I_i = PINV\overline{INVTOTAL} \quad (\mathbf{A29})$$

$$\sum_{i=1}^{27} \overline{PFX}EXP_i - \sum_{i=1}^{27} \overline{PFX}IMP_i + \overline{NTFS_{RC}} + \overline{NTFS_{PS}} = \overline{D}(\mathbf{A30})$$

$$P_{sav}Q_{sav} + \overline{SAVPUB} - PINV\ \overline{INVTOTAL} = \overline{D}\ FC(\mathbf{A31})$$

Factor markets

While the equilibrium in the capital market is reflected in equation **(A9)**, the unemployment equilibrium in the labor market is reflected in **(A10)**, i.e. in the latter case there is an additional equation which reflects the existence of unemployment and the relationship between real wages and unemployment rate:

$$\frac{W}{IPC} = \left(\frac{1-U}{1-\overline{U}}\right)^{\frac{1}{\beta}} \quad (\mathbf{A32})$$

$$CPI = \frac{\sum_{i=1}^{27} \theta_i PO_i}{\sum_{i=1}^{27} \theta_i \overline{PO}_i} \quad (\mathbf{A33})$$

Endogenous variables

Symbol	*Definition*
A_i	Armington aggregate (total supply of goods) sector *i*
CFB_i	Final domestic consumption of good *i*
CFB_i^{SP}	Public final domestic consumption of good *i*
CFB_i^{RC}	Private final domestic consumption of good *i*
CPI	Consumer Price Index
EXP_i	Exports of sector *i*
FC	Conversion factor in local currency
I_i	Investment (gross capital formation) in goods produced by sector *i*
II_{ij}	Intermediate inputs of sector *j* used by sector *i*
IMP_i	Imports of goods from sector *i*
O_i	Production of sector *i* sold in the domestic market
OII_i	Collection of indirect taxes on production
OIP	Collection of indirect taxes on products (including VAT)
P_{sav}	Shadow price of savings
PA_i	Unit cost of Armington aggregate of sector *i*
$PCOGR_i$	Price of energy aggregate (except electricity) of sector *i*
PE_i	Price of energy aggregate of sector *i*
$PINV$	Unit cost of investment
PO_i	Unit cost of production of sector *i* sold in the domestic market
$PROFIT_i^A$	Unitary profit for A_i (depending on origin)
$PROFIT_i^{CET}$	Unitary profit for A_i (depending on destination)

$PROFIT_i^x$	Unitary profit for X_i
PVA_i	Unit costs of primary inputs used in sector *i*
$PVAE_i$	Unit costs of value added and energy used in sector *i*
PX_i	Price of goods produced in sector *i*
Q_c	Demand for aggregate consumption
Q_{cg}	Consumer demand for aggregate goods
Q_l	Leisure demand
Q_{sav}	Savings demand
R	Unit rent of capital
SOC_i	Collection of social contributions paid by sector *i*
U	Unemployment rate
W	Wage
WF	Welfare
X_i	Production of sector *i*
Y_{RC}	Representative consumer disposable rent

Exogenous variables and parameters

Symbol	*Definition*
$\overline{BALPUB}$	Public sector balance
$\overline{D}$	External balance
$\overline{INVPUB}$	Public sector investment
$\overline{INVTOTAL}$	Total investment of the economy
$\overline{K}_{RC}$	Capital endowment of the representative consumer
$\overline{K}_{SP}$	Capital endowment of public sector
$\overline{L}$	Labor endowment
$\overline{NTPS}$	Net transfers from public sector to representative consumer
$\overline{NTFS}_{RC}$	Net transfers from foreign sector to representative consumer
$\overline{NTFS}_{SP}$	Net transfers from foreign sector to public sector
$\overline{PO}_i$	Price of good *i* in the base year
$\overline{PFX}$	Foreign prices
$\overline{SAVPUB}$	Public sector savings
$\overline{U}$	Unemployment rate in the base year
$\overline{Y}_{SP}$	Public sector revenue
a_i, b, c_{0i}, c_{ji}, d_i, e_i, f_{ik}, h_i, k_i	Parameters of participation
oip_i^{FBC}, oip_k^{CF}	Other indirect taxes on products, ad valorem, in sector *i*, levied on investment and final consumption, respectively
$oii_i^{II}, oii_i^{FBC}, oii_k^{CF}$	Other indirect taxes on production, ad valorem, in sector *i*, levied on intermediate inputs, investment and final consumption, respectively

soc_i	Social contributions, ad valorem, paid by sector *i*
$\alpha_i, \chi_i, \gamma_i, \zeta_i$	Scale parameters
β	Elasticity of transformation in sector *i*
φ_i	AEEI factor
θ_i	Share weights for CPI
ε_i	Elasticity of transformation in sector *i*
σ_i^A	Armington elasticity of substitution in sector *i*
σ^{CL}	Elasticity of substitution between consumption and leisure
σ_i^{LK}	Elasticity of substitution between labor and capital in sector *i*
σ_i^{LKE}	Elasticity of substitution between value added and energy in sector *i*
$\tau_{ener}, \tau_i, \tau_{sav}$	Share parameters

APPENDIX II

Glossary:

AIEC: All inputs except coal

CGR: Coal, Gas, Refining

COGR: Coal, Oil, Gas, Refining

ECOR: Electricity, Coal, Oil, Refining

K: Capital

KLEEO: Capital, Labor, Energy, except Oil

L: Labor

RI: Rest of Inputs

RII: Rest of Intermediate Inputs

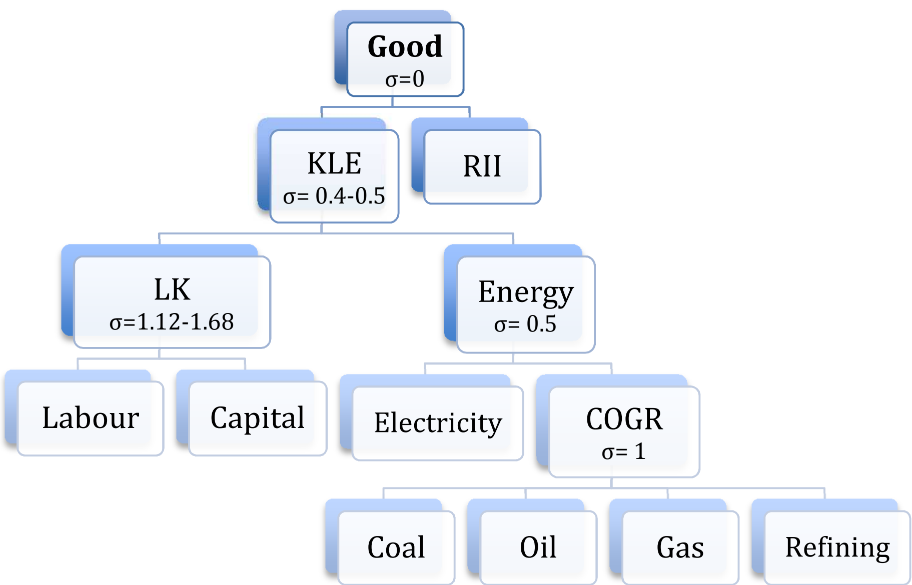
RIIEE: Rest of Intermediate Inputs except Energy

RIIEEO: Rest of Intermediate Inputs except Energy and Oil

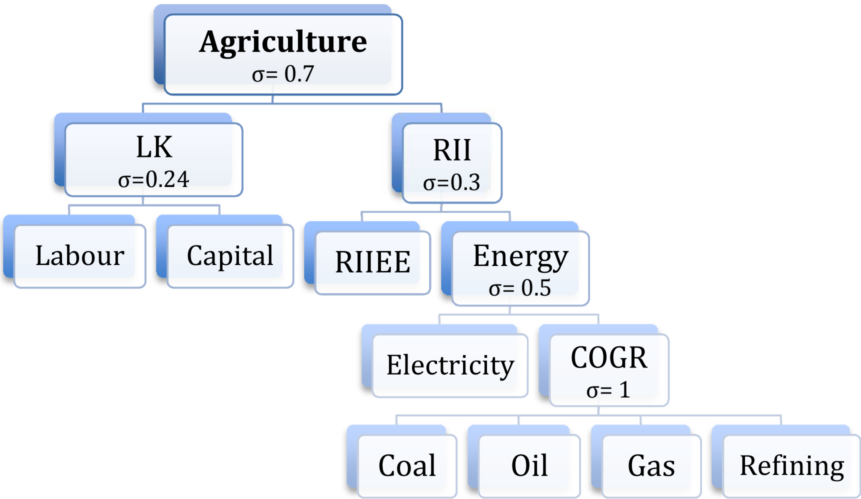
RIIEO: Rest of Intermediate Inputs except Oil

Nested production functions

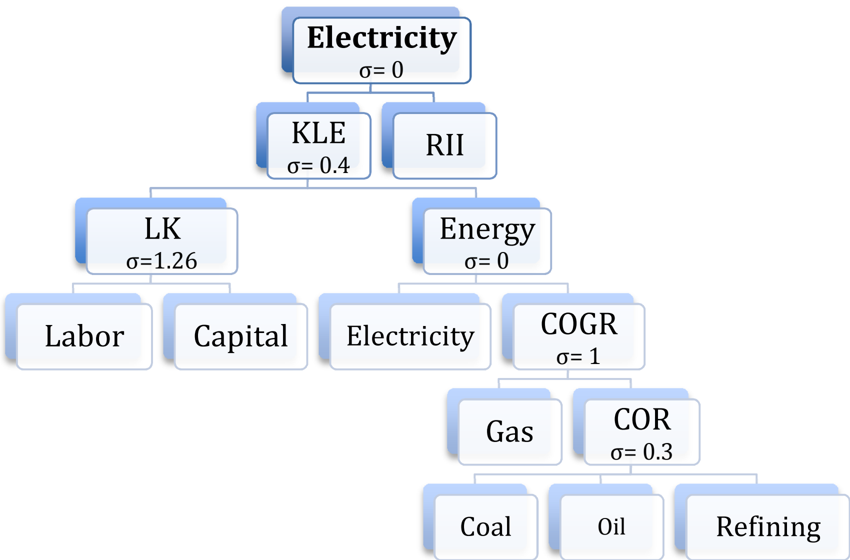
- All sectors except energy sectors and agriculture:



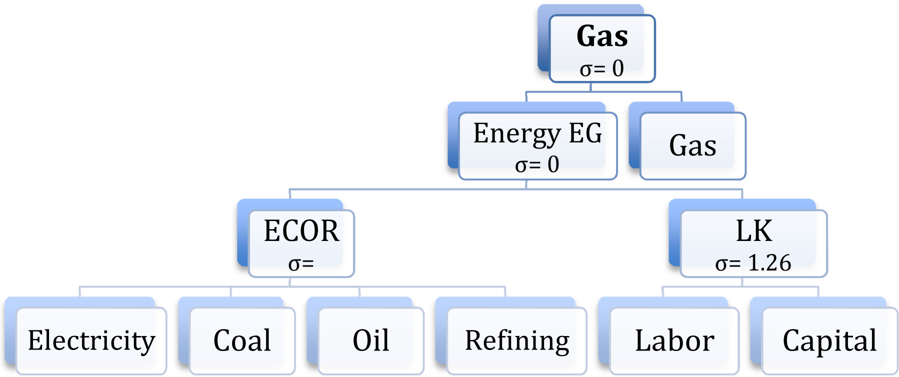
- **Agriculture**: Agriculture, Livestock and Fisheries.



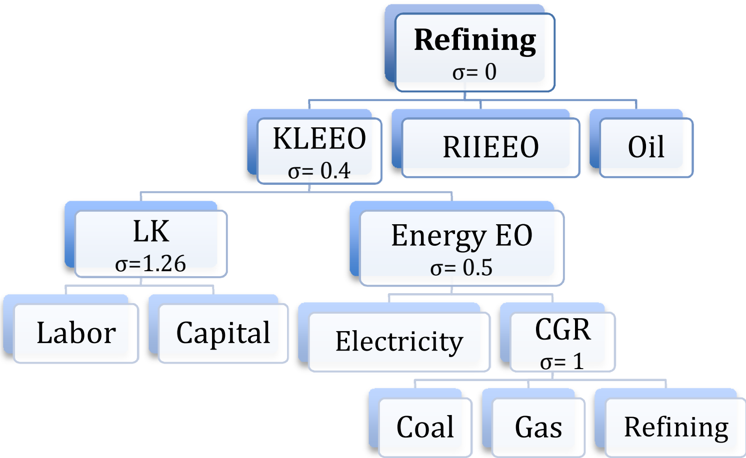
- **Electricity**: Production and distribution of electricity



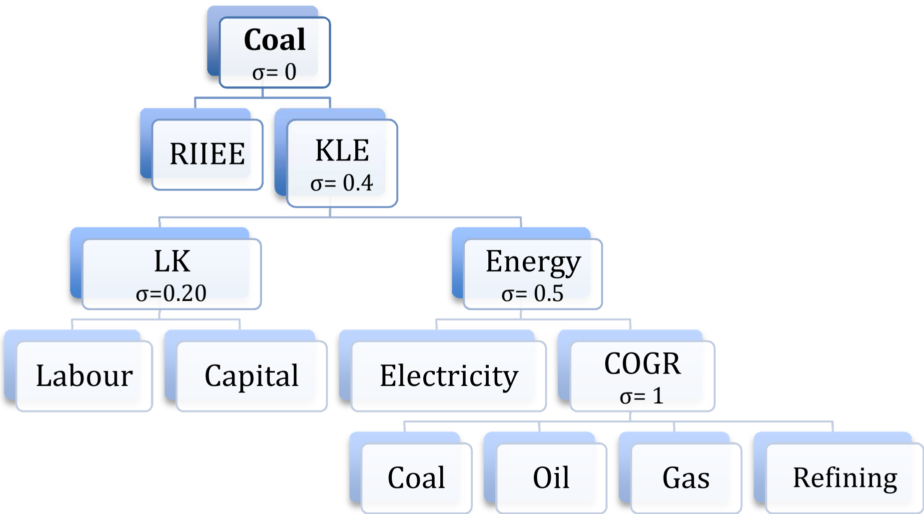
- **Gas**: Production and distribution of gas.



- **Refining**: Manufacture of coke, refined petroleum products and nuclear fuel.



- **Coal**: Extraction of coal, lignite and peat.



Nested utility function: