# RETHINKING ECONOMY-WIDE REBOUND MEASURES:

# AN UNBIASED PROPOSAL

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### *Abstract*

In spite of having been first introduced in the last half of the ninetieth century, the debate about the possible rebound effects from energy efficiency improvements is still an open question in the economic literature. This paper contributes to the existing research on this issue proposing an unbiased measure for economy-wide rebound effects. The novelty of this economy-wide rebound measure stems from the fact that not only actual energy savings but also potential energy savings are quantified under general equilibrium conditions. Our findings indicate that the use of engineering savings instead of general equilibrium potential savings downward biases economy-wide rebound effects and upward-biases backfire effects. The discrepancies between the traditional indicator and our proposed measure are analysed in the context of the Spanish economy.

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## *1. Introduction: to Rebound or not to Rebound, still an open debate*

During the last few years policies that seek to promote lower use of energy have been getting increasing attention. This growing interest stems from the desirability of taking into account the negative impact of economic activities on the natural environment, i.e. the so-called 3-E interaction. Therefore, the main goal of policies that aim at reducing the use of energy in the production process is "decoupling", that is to say, the limitation of the interrelationship between economic growth and environmental degradation. The policy instruments for trying to achieve this goal are of three broad types: pricing policies that use environmental taxation, regulatory policies, and energy efficiency policies. According to the International Energy Agency (IEA), energy efficiency gains and energy savings should be able to contribute up to 43 percent to overall reduction in energy use. Among these policies, energy efficiency policies turn out to be the most effective policy tool. The reason behind this is that we consume energy services and not energy itself. Thus it is always possible to do "the same with less". For doing so, we bring into play "ideas" in the form of technological enhancements that help societies to maintain their life standards, and even improve them, using less resources and/or implementing better allocations (Simon, 1981).

However, and differently to the other alternative policy tools mentioned above, in the case of energy efficiency policies substitution effects will work in the opposite direction: energy productivity gains push down energy effective prices therefore increasing the attractiveness in the use of this input in the production process which in turn leads to the substitution of less pollutant inputs by energy. Consequently, it is also plausible "to do more because it is less costly". Additionally, if prices of energy goods, i.e. prices of fuel, do not change, reductions in effective and/or actual prices of this input, i.e. prices of energy services, lead to output/competitiveness, composition and income effects. The sum of all these effects acts to offset the decreases in energy consumption that accompany pure efficiency effects (Turner, 2009). This implies that part or even all initial energy savings expected by the policy might be lost. Therefore it is not necessarily certain that using energy more efficiently reduces the demand for it proportionally. The "Rebound-Effect" is the way to quantify this impact (Jevons, 1865; Khazzoom, 1980; Brookes, 1990; Saunders, 1992, 2000a, 2000b; Schipper, 2000), also known as the "Khazzoom-Brokes" postulate. Therefore, and despite the fact that energy efficiency policies will boost economic growth and will favour the trade balance, if rebound effects are at work these policies might loose its effectiveness when trying to reduce the intermediate energy use and its derived emissions levels.

The typology of these perverse effects is well defined and is commonly accepted among rebound economists. Following Greening *et al* (2000) and Sorrell (2007) there is a three-part rebound classification that encompasses both partial and general equilibrium views of this effect: (a) *Direct Rebound effects:* they are based upon partial equilibrium conditions and are the result of pure price effects; (b) *Indirect Rebound effects:* they first originate from the pure price effects that cause direct rebound effects that, thanks to economic linkages, are further transmitted throughout the whole economic system. Consequently, these indirect rebound effects belong to a general rather than a partial equilibrium perspective; and (c) *Economy-wide Rebound effects*: they track down the impact that the decline in the effective price of energy that stems from energy efficiency gains has over the aggregate demand for energy in the economy. They are therefore based upon a pure general equilibrium perspective that considers both direct and indirect rebound impacts.

Despite the long academic debate and the abundant empirical research on rebound effects, a consensus regarding the existence and the magnitude of rebound mechanisms has yet to be reached. The problems in testing the existence and the size of direct and indirect rebound effects stems from the fact that there is not a unique definition of energy efficiency, i.e. Hicks Neutral versus Hicks Non-Neutral Technical change, and the resulting difficulties in measuring “pure” changes in energy consumption from efficiency gains. Apart from the problems that relate to the explanatory and the explained variable, simultaneity might also be at work: changes in energy consumption might also affect changes in energy efficiency due to variations in behaviour as a consequence of the implementation of specific policies and historical economic events (Meyer, 1995; Frondel and Schmidt, 2005). As stated by Sorrell (2007) and Schipper and Grubb (2000), these definitional issues together with the problem of simultaneity might have relevant implications for estimating direct and indirect rebound effects leading to biased measures and thus to arguable conclusions.

Differently to econometric methods, computational general equilibrium models (CGE models) allow measuring economy-wide rebound effects that account for both direct and indirect mechanisms. Under the CGE approach rebound effects are evaluated rather than estimated and tested, as it is common in econometrics studies. Both empirical approaches to rebound effects, CGE and econometric techniques, share the same source of bias mentioned above with the exception of simultaneity. CGE models have the advantage of maintaining the appropriate relation of causality and isolating the effects of energy productivity gains from the influence of other possibly confounding variables. The reason is that the evaluation techniques of CGE models allow for the exogenous simulation of these efficiency improvements.

The CGE approach, however, has its own sources of biases. Examples arise from the deterministic process of parameter calibration, assumptions on agents' rules of behaviour, and the functioning of primary factors markets. These potential sources of bias for economy-wide rebound measures, though relevant, might be partially resolved applying sensitivity analysis with respect to key parameters and/or using more flexible assumptions. There is another type of bias, however, that has not been pointed out by previous literature, and that consequently has not been sorted out yet. It has to do with the way that economy-wide rebound measures are computed under the CGE methodology. Indeed, the wedge between potential and actual energy savings are not usually measured under the same equilibrium conditions. Previous analysis of economy-wide rebound effects have considered that potential energy savings correspond, exactly, with what has been termed engineering energy savings. But this is not the case when market interdependencies are present, which are in fact the main distinction between partial and general equilibrium conditions.

The main focus of this paper is therefore to define and propose an unbiased economy-wide rebound effect measure whereby both potential and actual energy savings are quantified under the same equilibrium conditions. This novel economy-wide rebound measure considers that potential energy savings under a general equilibrium scenario occur only when considering quantity adjustments, with no price effects at work. In this case, consequently, price shocks that lead to rebound impacts are omitted. General equilibrium conditions are nevertheless maintained since market interdependencies are controlled for. In constructing this unbiased measure of potential energy savings, we rely on input-output (IO) analysis since in this modelling set-up price effects can easily be isolated from quantity effects. Or results indicate, firstly, that the discrepancies between the biased and unbiased economy-wide measures are significant and, secondly, they have a strong sensitivity with respect to the energy elasticity of substitution parameter. The use of engineering savings, instead of general equilibrium potential savings, downward-biases potential economy-wide rebound effects and upward-biases potential backfire effects.

The remaining of this paper is organised as follows. In Section 2 we present the source of bias that we want to deal with in this analysis and the definition of our unbiased proposal for measuring Economy-Wide rebound effects. Section 3 briefly describes the methodology used to obtain this novel unbiased economy-wide rebound measure. Section 4 contextualises our discussion using an empirical exercise for the Spanish economy. Section 5 concludes. An Appendix detailing the characteristics of the CGE model is also added as background reference.

## *2. Defining an Unbiased Measure of Economy-wide Rebound Effects*

### *2.1. A General Definition of the Rebound*

In order to introduce the economic concept of the rebound effect, we present its definition as price elasticity[1] (Khazzoom, 1980; Berkhout *et al*, 2000; Binswanger, 2001; and Greene *et al,* 1999a). We first make a distinction between energy in natural units, *E*, measured by kWh or PJ [2], and energy in effective or efficiency units, $\varepsilon$, that is, the amount of energy services obtained per unit of physical energy used. To transform energy in natural units to effective units, we have an energy augmenting factor denoted by $\tau$ that represents "human ideas", in other words, technology:

$$\varepsilon = E \cdot \tau \quad with\ \tau \geq 0 \tag{1}$$

This implies that the percentage change in energy use measured in efficiency units is the sum of the percentage change in physical energy use and energy-augmenting technological progress:

$$\frac{d\varepsilon}{\varepsilon} = \frac{dE}{E} + \frac{d\tau}{\tau} \tag{2}$$

Expression (2) indicates that if there is a *X* percent improvement in energy efficiency, i.e. a positive change in $\tau$, without any change in physical quantities, the effective energy use will be *X* percent higher. In other words, energy productivity in physical units has increased, since the amount of energy services per unit of natural energy has increased. As mentioned in the introduction, a central issue in the rebound analysis is the fact that, provided the price of energy in physical units remains constant, any change in energy efficiency will have a corresponding impact on the effective price of energy, when measured in efficiency units. Specifically:

[1] There is another definition of the rebound effect related to the efficiency elasticity. The difference between defining the rebound in terms of price elasticities and in terms of efficiency elasticity stems from the assumption behind them. Under the former, the price of physical energy is exogenous, thus they are independent upon efficiency gains. See Sorrell and Dimitropoulos (2007) for a more detailed description of the possible definitions of rebound and the implications in econometrics work.

[2] The acronyms Kwh and PJ refer respectively to kilowatt hour and picojoule. They are standard units in measuring energy consumption. One Kwh corresponds to 3.6 $10^6$ joules while one picojoule corresponds to $10^{-12}$ joules.

$$\frac{dp_{\varepsilon}}{p_{\varepsilon}} = \frac{dp_E}{p_E} - \frac{d\tau}{\tau} \quad \text{and} \quad \frac{dp_E}{p_E} = 0 \Rightarrow \frac{dp_{\varepsilon}}{p_{\varepsilon}} = -\frac{d\tau}{\tau} \tag{3}$$

With constant physical energy prices, we expect the fall in the price of energy in efficiency units to generate an increase in the demand for energy in efficiency units. This is the source of the rebound effect. In general:

$$\frac{d\varepsilon}{\varepsilon} = -\eta_{\varepsilon} \frac{dp_{\varepsilon}}{p_{\varepsilon}} \quad \text{with } \eta_{\varepsilon} \geq 0 \tag{4}$$

Where $\eta_{\varepsilon}$ is the general equilibrium price elasticity of demand for energy in effective units. This elasticity may refer to different users of energy within the economy (i.e. households as well as producers), different uses of this input (i.e. heating and lightning), and different equilibrium conditions (i.e. isolated market or economy-wide perspective). The change in energy demand in natural units derived from productivity gains can be found by substituting expressions (3) and (4) into expression (2), giving:

$$\frac{dE}{E} = (\eta_{\varepsilon}^{\tau} - 1)\frac{d\tau}{\tau} \tag{5}$$

For an efficiency increase of $d\tau$ that applies to all energy use, rebound, *R*, expressed in percentage terms, is defined as:

$$R = \left(1 + \eta_E^{\tau}\right)100 \quad \text{with} \quad \eta_E^{\tau} = \frac{dE/E}{d\tau/\tau} \tag{6}$$

The rebound indicator *R* measures, in relative units, the extent to which the change in energy demand fails to fall in line with the increase in energy efficiency. Relative changes in energy in natural units refer to actual energy savings generated by efficiency gains, while proportional variations in productivity are termed as potential energy savings. When rebound is equal to 0 percent, a change in energy efficiency produces an equivalent proportional decrease in energy use. Rebound values less than 100 percent but greater than 0 percent imply that there has been some preservation of actual energy saving as a result of the efficiency improvement, but not by the full extent of the efficiency gain, i.e. if a 5 percent increase in energy efficiency generates a 4 percent reduction in energy use, this corresponds to a 20 percent rebound. Rebound values greater than 100 percent imply positive changes in energy use measured in natural units. This means that, apart from eroding all potential energy savings, the decline in the effective price of energy has increased even further the initial levels of energy consumption. This is an extreme case of the rebound that is termed in the literature as backfire effect.

The rebound effect is therefore the proportional wedge between potential energy savings and actual energy savings due to the reaction in price variations. If expression (5) is substituted into identity (6), the link between rebound and the elasticity of demand for energy is made clear:

$$R = \eta_{\varepsilon} 100 \qquad (7)$$

In Table 1 we summarise the relationship between price elasticity values and the different rebound scenarios. If the elasticity is zero, the fall in energy use equals the improvement in efficiency and rebound equals zero. If the elasticity takes a value between zero and unity, meaning that energy demand is relatively price-inelastic, some rebound effect is present because potential energy savings are partially lost. If the demand is relatively price-elastic, an improvement in energy efficiency boosts even more energy demand. With a price-elastic demand for energy, rebound is greater than 100 percent hence leading to back-fire effects.

*Table 1: Rebound Effect Scenarios.*

| Price Elasticity | Rebound Effect | Implication for Potential Energy Savings |
|---|---|---|
| *Perfectly inelastic*<br><br>$\eta_\varepsilon = 0$ | *No Rebound*<br><br>*R=0%* | ***All** Potential Energy Savings are preserved:*<br>$\frac{dE}{E} = -\frac{d\tau}{\tau}$ |
| *Relatively Inelastic*<br><br>$0 < \eta_\varepsilon < 1$ | *Positive Rebound*<br><br>*0 <R<100%* | ***Some** Potential Energy Savings are preserved:*<br>$\frac{dE}{E} < 0$<br>*but* $\frac{dE}{E} < -\frac{d\tau}{\tau}$ |
| *Elastic*<br><br>$\eta_\varepsilon > 1$ | *Backfire effect*<br><br>*R>100%* | *The energy efficiency improvement leads to an **increase** in the demand for energy in natural units:*<br>$\frac{dE}{E} < 0$ |

### *2.2. A General Equilibrium Definition of the Rebound: An Unbiased Proposal*

Rebound effects refer to the relative distance between potential and actual energy savings, *PES* and *AES* thereafter. Also, all empirical results on economy-wide rebound effects reported by previous research stem from the assumption that energy productivity gains exactly refer to potential energy savings. In these analyses rebound effect measures have been computed directly from expression (6) above. Rewriting this expression in terms of potential and actual energy savings, we obtain:

$$R = \left(1 + \frac{dE/E}{d\tau/\tau}\right) = \left(1 + \frac{AES}{PES}\right) \tag{8}$$

If energy productivity improvements are exogenous, a most common assumption when measuring rebound impacts from energy efficiency improvements, expression (8) implies that potential savings are identical to productivity gains in a partial equilibrium framework, but this is not the case under a general equilibrium perspective whereby potential energy savings are expected to be larger than productivity improvements.

As an illustration to this distinction, we define and compare formally potential energy savings under the two aforementioned possible equilibrium scenarios. In a partial equilibrium analysis, if energy productivity increases exogenously by *X* percent, potential energy savings would correspond to that *X* percent because there is not any derived effect in interrelated markets, i.e. prices and quantities of non-energy sectors remain constant. If an economy produces *N* commodities under a partial equilibrium framework the expression for potential energy savings ($PES^{PE}$), other things held constant, is given by:

$$PES^{PE} = \sum_{i=1}^{N} \left[ \frac{1}{E_i} \frac{\partial E_i}{\partial \tau_i} \bigg|_{\overline{P},\overline{Q}} \right] \qquad \forall i \in N \tag{9}$$

Here $E_i$, $\tau_i$ and $\overline{P}$ denote, respectively, sectoral energy input demand, energy efficiency gains, and a market price vector. $\overline{Q}$ refers to the market quantity vector not including the energy sector where efficiency improvements occur. *N* refers to the number of productive units in a specific economy. As mentioned before, in a partial equilibrium framework it is assumed that changes in prices or/and in quantities in market *i* do not affect the remaining commodities' markets. Therefore under these equilibrium conditions, energy efficiency improvements that would reduce the demand for energy inputs would only have an impact over the energy sector but not over its interrelated sectors, i.e. sectors that provide inputs to the energy sector. General equilibrium potential energy savings do consider, however, the aforementioned interdependencies.

Consequently, expression (9) above is inappropriate for measuring potential energy savings under a general equilibrium framework. Potential energy savings should be rather defined as those energy savings that occurred when price effects are omitted, i.e. if all prices are held constant and so no rebound mechanism is at work. In fact, this price mechanism is what explains the wedge between actual and potential energy savings that leads to rebound effects. Nevertheless, in a general equilibrium context, even when prices are held constant, productivity improvements in energy inputs lead to quantity effects in interconnected markets. If there is an improvement in the degree of productivity of energy inputs, this would lead to a decline in the production of energy and thus to a decline too on the intermediate inputs used by this sectors. This, in addition, would affect in a similar way the output levels of interrelated sectors. Therefore, when prices are held constant in a general equilibrium context, energy productivity improvements generate multiplicative effects in quantities that should be taken into account when measuring potential energy savings. Thus the appropriate measure of economy-wide potential energy savings ($PES^{GE}$) should be:

$$PES^{GE} = \frac{1}{E}\frac{dE}{d\tau}\bigg|_{\bar{P}} \tag{10}$$

As we can assert easily from expressions (9) and (10), notice that under a general equilibrium context is straightforward that potential energy savings do not coincide with productivity gains. The consequence to the economy-wide rebound effect measure is that using the percent improvement in energy productivity as potential energy savings downward-biases (upward-biases) economy-wide rebound (backfire) effects. In this sense, most often "rebound economists" making use of the CGE framework, have been computing economy-wide rebound measures as 1 plus the simulated proportionate change in total energy input used under the CGE approach ($AES^{GE}$) divided by the evaluated proportionate change in energy efficiency ($PES^{PE}$):

$$R^b = \left[1 + \frac{AES^{GE}}{PES^{PE}}\right] \times 100 \tag{11}$$

Expression (11) is still a biased measure of economy-wide rebound effects because, differently to a partial equilibrium context, potential energy savings do not coincide with the evaluated proportionate change in energy efficiency. Due to sectors' interdependencies, under general equilibrium conditions the evaluated proportionate changes in energy efficiency are expected to be higher than those corresponding to partial equilibrium conditions. This is true even though price effects are omitted and only quantity effects from energy efficiency gains are considered.

Differently to (11), the simulated proportional change in total energy input, or actual energy savings, is made relative to the economy-wide decline in this input when prices are held constant $(PES^{GE})$ but market interdependencies are controlled for. It now reads as:

$$R^u = \left[1 + \frac{AES^{GE}}{PES^{GE}}\right] \times 100 \qquad (12)$$

In our proposed unbiased economy-wide rebound measure ( $R^u$ ) both actual and potential energy savings correspond to general equilibrium measures. In homogenising both measures, we propose the combined use of the Leontief quantity model and the CGE approach. To obtain an appropriate and unbiased measure of the economy-wide rebound effect, the denominator $PES^{GE}$ in expression (12), which corresponds to expression (10), is obtained using the IO approach. This allows us to isolate quantity from price effects making it possible to derive a general equilibrium measure of potential energy savings. The way this novel economy-wide measure is computed is explained in more detail in the following section.

## *3. Methodology: CGE Models and Unbiased Measures of Economy-wide Rebound Effects.*

The IO framework (Leontief, 1941) can be seen as an adaptation of general equilibrium analysis that captures the existing quantity interdependencies between interrelated economic activities and does so in an easily described way using a set of linear equations. The quantitative information used in this type of analysis comes from the well-known Input-Output tables that are regularly assembled by Statistical offices. These tables supply detailed data on the transactions of good and services, distinguishing between intermediate and final demand uses, as well as providing the structure of production costs in terms of intermediate costs and value-added. However, they only contain information about the net income generated in each production sector, but not about its owners. This implies that the circular flow of income cannot be fully reflected in Input-Output analysis since the existing income-expenditure interactions are neither incorporated nor considered.

In order to include these interactions, Input-Output tables are extended with additional information that fills the aforementioned gaps and leads to the construction of so-called Social Accounting Matrices (SAMs). SAMs are very useful as the numerical backbone for the implementation of CGE models (Scarf, 1967; Shoven and Whalley, 1984). These models combine the theoretical Arrow-Debreu framework with the statistical information contained in a given SAM, creating a micro-consistent approach in which all the market interactions are price-dependent. The numerical implementation is referred in the literature as calibration (Mansur and Whalley, 1984).

In fact, both IO and CGE frameworks are useful to guide specific policy decisions and both can be used to analyse a large variety of economy-wide issues such as trade policies, fiscal reforms, environmental policies, and technological change, among others. According to the above definitions, input-output analysis is more limited than CGE models and it can be considered as a simplified version of the former (i.e. in CGE models quantities and prices are mutually inter-connected while in Leontief's model these two set of variables are independent of each other and a version of the classical dichotomy applies). The simplicity of IO analysis, however, has the benefit of isolating the role played by specific interactions in the economy, i.e. inter-industry linkages and/or price effects. Thus, as a first approximation, it provides a simpler understanding of these particular interactions within the more complex ones as are those captured by the CGE framework where prices and quantities are mutually inter-connected.

When dealing with the derived economy-wide effects of efficiency changes, IO analysis is quite useful since it provides a simple but clear-cut mechanism to ascertain how efficiency improvements taking place in a specific sector spread throughout the economy and, thanks to the existing interactions among sectors, end up influencing the rest of sectors. Data on intermediate input efficiency or productivity stems from input/output proportions that are obtained from IO tables. These proportions are known as Leontief direct input-output coefficients and are contained in a matrix $A$ known as the structural matrix.

### *3.1. Potential Energy Savings under General Equilibrium Conditions*

Under the classical Leontief model, production in each sector $X_i$ is a function of the technical coefficients contained in the structural matrix and final demand flows contained in a column vector $f$ :

$$X_i = \phi(a_{ij}, f_j) \quad \forall i, j \in N \quad a_{ij} = \left[A\right]_{ij} \text{ and } \quad f_j = \left[f\right]_j \tag{13}$$

As long as the structural matrix presents the appropriate properties, i.e. the matrix $(I - A)$ is non-singular and the productivity of matrix $A$ with respect to all non-negative column vectors of final demand $f \geq 0$ is fulfilled expression (13) represents a system of equations with a unique solution. The implication of this expression is that any exogenous change in final demand levels and variations in technical coefficients have an endogenous impact over all sectoral output levels.

According to (13), exogenous improvements in energy efficiency would lead to exogenous changes ( $\tau_j - 1$ ) in those technical coefficients that relate to the intermediate use of inputs coming from the energy sector ($E$) while the other coefficients remain constant:

$$X^{'}_i = \phi(a_{ij} - \left(\tau_j - 1\right) a_{ij}, f_j) \quad \text{where } \tau_j > 1 \quad \text{if } E = i \text{ and } \tau_j = 1 \quad \text{if } E \neq i \tag{14}$$

Knowing the initial or potential energy efficiency shock we want to evaluate, i.e. $\tau_j - 1$, and using data on the symmetric input-output table of an specific economy, potential energy savings under general equilibrium conditions are given by:

$$PES^{GE} = X'_E = \phi(a_{ij} - \left(\tau_j - 1\right) a_{ij}, f_j) \tag{15}$$

***Table 2**: Potential General Equilibrium Savings from the Spanish SIOC-04 with a 5% efficiency improvement in the intermediate use of energy.*

| **Energy Sectors** | **% decline in intermediate input demand** | **% decline in total output** | **% decline in $CO_2$ emission levels** |
|---|---|---|---|
| ***2. Extraction of Anthracite, Coal, Lignite and Peat*** | 8,688 | 8,566 | 8,560 |
| ***3. Extraction of Crude, Natural Gas, Uranium and Thorium*** | 8,554 | 8,528 | 8,520 |
| ***5. Coke, Refinery and Nuclear fuels*** | 6,116 | 3,553 | 0,044 |
| ***6. Production and Distribution of Electricity*** | 5,926 | 4,504 | 3,553 |
| ***7. Production and Distribution of Gas*** | 6,779 | 5,008 | 21,470 |
| ***Economy-wide effect*** | ***6,867*** | ***5,134*** | ***7,808*** |

Table 2 summarises the results for $PES^{GE}$ under a 5 percent improvement in energy efficiency in the intermediate use of this input. From these findings, in a general equilibrium context, potential energy savings are remarkably above the evaluated proportionate change in energy efficiency, i.e. the former represents almost 40 percent over the latter. This is explained by the negative multiplicative effect that the decrease in energy input use has over its inter-connected markets. A decline in the intermediate use of energy also leads to a reduction in its intermediate input demand affecting output levels of those sectors that provide inputs to the energy block. This, at the same time, pulls down even more energy input demand. Since $PES^{GE} > PES^{PE}$ the use of (11) instead of (12) downward-biases economy-wide rebound effects and upward-biases backfire and super-conservation effects. The same procedure has been used when computing the economy-wide rebound effect in terms of $CO_2$ emission levels. We will illustrate and justify empirically the latter statement in section 4 of this paper.

### *3.2. Actual Energy Savings under General Equilibrium Conditions*

We have relegated the details of the CGE modelling approach, background data and calibrated elasticities for Spain in 2004 to the Appendix.

The energy efficient shock introduced in the CGE approach to evaluate actual energy savings under general equilibrium conditions ( $AES^{GE}$ ) is undertaken by increasing the productivity of the energy composite by 5 percentage points, i.e. $\tau_i = \tau = 1.05$ in the production structure presented in expression A.2 in the Appendix. This energy efficiency shock is homogenous for all of the 16 production sectors that we consider (see table AP1 in the Annex). The choice of this technology structure relies on the conclusions of the empirical analysis by Vega-Cervera and Median (2000). Even though the study of these authors appear to be a consistent analysis of the hierarchical KLEM structure for the Spanish case, more research should be done since it is not yet completely clear how energy combines with the other production inputs in the economy. This limitation was also recognised by the authors themselves.

As mentioned above, this is a one-off exogenous (and costless[3]) energy augmenting technological progress (i.e. increasing units of output produced per unit of energy input). Note that in this analysis, we apply the efficiency shock only to the use of domestically supplied energy, and not on imported energy inputs.

One of the characteristics that differentiate input-output analysis from the CGE approach is that the effects on prices and quantities are simultaneously independent. In the context of rebound effects from energy efficiency gains, this allows isolating the cause that is a price effect, i.e. the decline in the effective price of energy from the consequence that relates to a quantity effect, i.e. the erosion of potential energy.

[3] Incorporating cost considerations when introducing an energy efficiency improvement will affect the nature and size of rebound effects (see Allan et al, 2007; Sorrel, 2007), as will the precise nature of its introduction. Here, in the first instance, the analysis is simplified by focussing on an exogenous and costless increase in energy efficiency. This is an important step as it allows us to consider the main basic drivers of the rebound effect (i.e. the general equilibrium responses to reductions in effective, and actual, energy prices) in isolation.

In the following section we present, compare and justify the distinction between unbiased and biased measures of the economy-wide rebound effect for the Spanish economy under a 5 percent hypothetical increase in energy efficiency in each production unit.

### *4. Biased versus Unbiased General Equilibrium Rebound effects: An empirical Exercise for the Spanish Economy.*

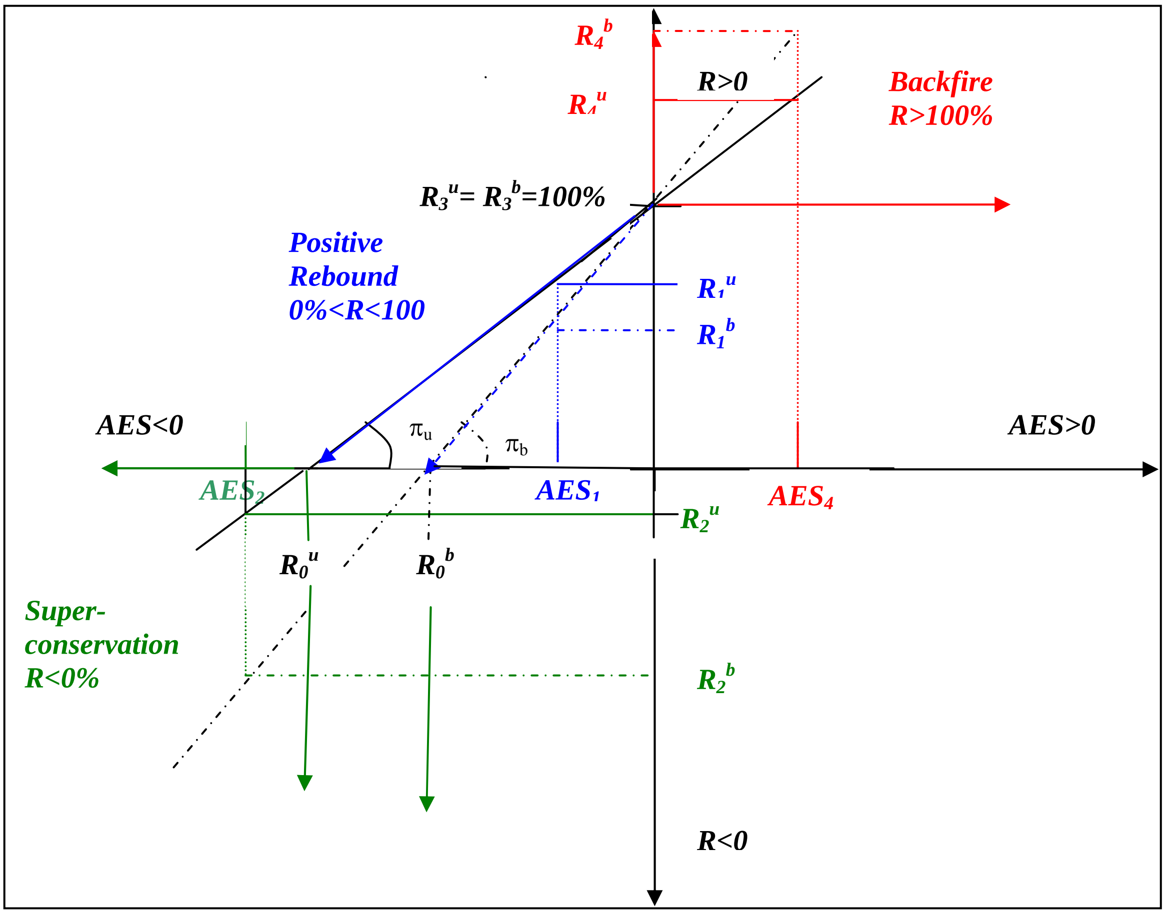
The unbiased and biased economy-wide rebound effect measures in terms of both energy and $CO_2$ emissions savings for a 5 percent simulated costless-exogenous improvements in energy efficiency under the KLEM specification in the production function (see expression A.2) are depicted in Table 3 where we have also included the distance between the unbiased and biased economy-wide rebound effect measures, i.e. $R^u - R^b$. This distance corresponds to the bias when *AES* and *PES* are not measured under the same equilibrium conditions. To show how the sign of this bias changes with respect to different *AES* values, we have varied in our simulations the elasticitity of substitution between value-added and energy, $\sigma_{VA,E}$. We have chosen this parameter of the upper nest in the KLEM specification in (A.2) to run the simulations in Table 3 because of its relevance in determining the size of economy-wide rebound effects (Sorrell, 2007, and Saunders, 2008). This elasticity plays a more relevant role in endogenously determining *AES* that the lower bound elasticity between Materials and the Value-added and Energy composite*, i.e.* $\sigma_{M,VAE}$.

***Table 3: % Rebound Measures in terms of energy and $C0_2$ emissions savings for 5% simulated costless-exogenous increase in energy efficiency***

| *Rebound Measures and Distance* | *Benchmark Elasticity Values* $\sigma^i_{VA,E}$ | | **Case1:** $\sigma^i_{VA,E}$ **increased by 5%** | | **Case 2:** $\sigma^i_{VA,E}$ **increased by 40 %** | | **Case 3:** $\sigma^i_{VA,E}$ **increased by 50 %** | |
|---|---|---|---|---|---|---|---|---|
| | **E** | ***$C0_2$*** | **E** | ***$C0_2$*** | **E** | ***$C0_2$*** | **E** | ***$C0_2$*** |
| $R^u$ | *81,962* | *106,772* | *84,960* | *107,850* | *106,178* | *115,458* | *112,316* | *117,316* |
| $R^b$ | *75,226* | *110,581* | *79,344* | *112,259* | *108,485* | *124,140* | *116,914* | *127,579* |
| $(R^u - R^b)$ | *6,736* | *-3,809* | *5,616* | *-4,409* | *-2,307* | *-8,682* | *-4,598* | *-10,263* |

As can be asserted from Table 3, the higher the elasticity of substitution between value-added and energy, the larger the economy-wide rebound effect. As was pointed out by previous empirical research (Allan *et al*, 2007, and Turner, 2008) the degree of concavity of the isoquants is positively related to the presence and size of the rebound effects of energy efficiency policies.

***Figure 1. Bias and Unbiased Rebound Measures as a function of Actual Energy Savings***




The reasoning behind the potential sign of the economy-wide bias is illustrated in Figure 1. In this figure, rebound effect measures are represented as linear functions of actual energy savings following expressions (11), i.e. $f_{R^b}$ and (12), i.e. $f_{R^u}$. According to these expressions, the slopes of these linear functions refer to the inverse of potential energy savings, i.e. $\pi_b$ and $\pi_u$. Again, since $PES^{GE} > PES^{PE}$ then $\pi_b > \pi_u$. As can be seen from Figure 1, under function $f_{R^b}$ if the simulated proportionate change in intermediate energy use turns to be negative *(AES<0)*, i.e. the intermediate use of energy has decreased due to the simulated energy efficiency gains, the decrease in the intermediate use of energy has to be lower to find no rebound. Consequently, for that range of *AES* values for which *AES<PES<0* and then *0<R<100* percent using expression (11) instead of (12) would lead to a downward bias of economy-wide rebound effects, i.e. $AES_1$ in Figure 1 where $R_1^u > R_1^b$. When $PES < AES < 0$ then $R > 100$ percent indicating a super-conservation scenario. In this case, if *PES* are measured under partial equilibrium conditions, this practise would lead to an upward bias of super-conservation effects, i.e. $AES_2$ in Figure 1 where $R_2^b > R_2^u$. Lastly, if energy efficiency gains increase further intermediate energy input demand, $AES > 0$, using the biased measure instead of the unbiased one would also lead to an upward bias of backfire effects, i.e. $AES_4$ in Figure 1 where $R_4^b > R_4^u$. The results obtained along this exercise back the conclusions obtained above in Figure 1. In this sense when economy-wide rebound effects are positive but lower than 100 percent the difference between the unbiased and biased measure is also positive. This means that the use of the biased measure would lead to a downward bias of economy-wide rebound effects. When economy-wide effects in terms of emissions and energy are higher than 100 percent, using the biased measure would upward bias backfire effects. These conclusions might alternatively be expressed in terms of elasticity. Therefore, if we use $R^b$ instead of $R^u$, technology needs to be more "elastic" to find no-rebound, or a super-conservation scenario, than when using $R^u$.

## *5. Conclusions*

The main target of this paper is to provide an unbiased measure of economy-wide rebound effects from energy efficiency improvements. Rebound effects represent the part of potential energy savings eroded when price mechanisms are at work. They represent the wedge between actual energy savings, which account for these price effects, and potential energy savings. To avoid bias in economy-wide rebound effects both potential and actual energy savings should be evaluated under general equilibrium conditions.

However, previous analysis have quantified actual and potential energy savings under different equilibrium scenarios, i.e. while actual energy savings correspond to general equilibrium effects, potential energy savings are computed under partial rather than general equilibrium conditions. This inconsistency generates a downward bias of potential economy-wide rebound effects and an upward bias of backfire effects.

As a solution for these two biases, we propose in this paper the combined used of two of the existing empirical general equilibrium models: the IO framework and the CGE approach. The IO model allows computing the point of departure when analysing economy-wide rebound effects, i.e. the potential energy savings under general equilibrium conditions. The IO quantity model is therefore an appropriate tool for quantifying economy-wide potential energy savings since price effects that lead to the erosion of energy savings are completely isolated. The CGE approach, in contrast, provides information about the actual energy savings under general equilibrium conditions because the effects of prices and quantities are simultaneously accounted for.

Besides formally defining this source of bias in economy-wide rebound effects measures and how it should be addressed, we have carried out an empirical exercise for the Spanish economy. Once hypothetical, exogenous, non-costly energy efficiency improvements are simulated for Spain, our results indicate that if we use the biased economy-wide rebound measure, technology needs to be more “elastic” to find no-rebound or a super-conservation scenario than when using our unbiased proposal.

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## APPENDIX

# Description and calibration of the CGE model of the Spanish Economy.

The CGE model for the Spanish economy used in section 3 includes $N$ =16 firms, four types of inputs in production, namely, capital, labour, energy and non-energy inputs, a representative household, a government sector, an account for corporations, corporations' sector, an external sector and a capital (savings/investment) account. Agents behave rationally and are profit and utility maximisers. No agent has significant market power. In our model and under the general aforementioned conditions, agents' behaviour is described as follows.

Related to production, a representative firm of each industry minimizes costs subject to technological constraints based upon constant returns to scale thus profits turn out to be zero. Perfect competitive markets are assumed. We follow the Armington (1969) assumption whereby imported products are imperfect substitutes for domestic production. To get sectors' final domestic output, production inputs (capital, labour, materials or non-energy inputs and energy) are combined within a succession of nested constant elasticity of substitution (CES) functions. 16 sectors and thus, commodities, are identified. 5 out of the 16 industries are energy supply sectors (see sector listing in Table A1 in the Annex). Two relevant production blocks are distinguished in the economy: the energy block (sectors 2-3 and 5-7) and the non-energy block (sectors 1, 4 and 8-16). Both blocks make use of a multi-level and sectors' homogenous technology.

Consumption activities refer to those of a single representative household. This representative household demands commodities and savings under an income constraint. Household income stems from selling labour and capital endowments plus net transfers from the government and firms.

The government produces a public consumption good, supports public investments and carries out income transfers to private sectors. All these government expenditures activities are financed through the collected taxes and, if necessary, with public deficit. Taxes are of two general types: a direct income tax and a range of indirect taxes (production tax, value-added tax, payroll tax on labour, and tariffs).

The corporations' sector acts as an intermediary sector that makes transactions with the rest of the economic agents in terms of property income, social contributions and transfers.

The foreign sector plays a residual but nonetheless necessary role for closing the model. We only distinguish in this analysis a unique foreign sector. Imports are demanded by the domestic industries and they are used to yield, along with domestic output, the total supply of goods. Part of this total supply is in turn demanded by the foreign sector as exports.

In equilibrium all markets clear with the exception of the labour market. All labour force in the economy is own by the representative household. Although the total supply of labour is fixed, this supply conform two parts, one related to active labour being demanded by firms and another that is idle and is interpreted as unemployment. The unemployment rate is made endogenous using a wage curve that relates unemployment to the level of the real wage rate in the economy.

This is the general description of the model. In the following sections we present the details about the agents' behavioural assumptions, the closure rule, equilibrium conditions and how the model is calibrated.

### A.1 *Firms' Production Activities*

#### *Domestic and foreign production*

In the production of gross output we assume a partial degree of substitution between domestic and imported goods. Thus for tradable goods total output in each production sector $i$ is a composite between domestic ($X_{D_i}$) and imported productions ($X_{M_i}$) obtained throughout a CES technology:

$$X_i = \left[ (a_{D_i} X_{D_i})^{\rho_i} + (a_{M_i} X_{M_i})^{\rho_i} \right]^{1/\rho_i} \qquad i \in T \subseteq N \quad N=16 \qquad \text{(A.1)}$$

Where, $a_{D_i}$, $a_{M_i}$ and $\rho_i$ are, respectively, the domestic and foreign input technical coefficients and the exogenous parameter that determines the elasticity of substitution between both, known as Armington elasticity. In our model we consider different Armington elasticities for the energy and non-energy block though homogenous within blocks. Additionally, the assumption of a small economy makes world prices to be exogenously determined.

***Domestic Production: Possible KLEM specifications***

Production of the domestic good $X_{Di}$ in each sector *i* is structured using a KLEM (Capital, Labour, Energy and Materials) nested production function. The Energy and Materials composite inputs are introduced along with capital (K) and Labour to the nested KLEM production function in four alternative ways, corresponding to the following configuration: in order to obtain the non-energy value-added (VA) input, conventional Capital (K) and Labour (L) are combined first.

$$\begin{aligned} VA_i &= \left( \delta (A_K K_i)^{\rho_{K,L}} + (1-\delta)\left(A_L L_i\right)^{\rho_{K,L}} \right)^{1/\rho_{K,L}} \\ VAE_i &= \left( \beta (\tau E_i)^{\rho_{VA,E}} + (1-\beta) VA_i^{\rho_{VA,E}} \right)^{1/\rho_{VA,E}} \\ X_{Di} &= \left( \alpha (A_M M_i)^{\rho_{M,VAE}} + (1-\alpha) VAE)_i^{\rho_{M,VAE}} \right)^{1/\rho_{M,VAE}} \end{aligned} \qquad \text{(A.2)}$$

Factor efficiency is input specific and represented by $A_j$ for each of the capital, labour and materials inputs, which remains constant in the simulations presented in this paper. In this chapter we simulate energy efficiency gains, which take place in the energy composite and are reflected in the parameter $\tau$ .

For simplicity, the non-energy Materials input composite for each sector *i* is a Leontief combination of the 11 non-energy inputs identified in Annex (Table A.1.) For the same reasons, the composite Energy input is a Leontief of five energy sources, specifically the outputs of the five local energy supply sectors. Future research will relax the latter assumption introducing imperfect substitution between primary and secondary energy inputs (Böhringer, Ferris and Rutherford, 1997) and between renewable a non-renewable.

This is a short-run model where the supply of capital is fixed, but while population and the participation rate are fixed, we have unemployment in our initial equilibrium .This introduces some flexibility in the labour supply. We assume a wage curve (see Blanchflower and Oswald, 1990, 1995) that reflects the relationship between real-wages and unemployment, so that unemployment and labour demand are endogenous while the total supply of labour is held fixed. The specification of the wage curve is given by:

$$w / cpi = u^{\beta} \tag{A.3}$$

where:

$$w / cpi = real \quad wages$$
$$u = unemployment\ rate$$
$$\beta = relation \qquad real\ wage - unemployment$$

***Corporations***

The account for Corporations is quite commonly present in many SAM's. It reflects the empirical reality that business surplus is not always fully distributed in first instance to asset holders as capital income. Part of it is assigned as property income and this account keeps track of these transfers to avoid leakages in the SAM. Its role in the subsequent modelling is immaterial. Since any account in a SAM can be seen as a budget constraint, we will stick to this tradition for the inflows and outflows of this especial account.

As mentioned above, the account for Corporations plays a simple "book-keeping" role for some income assignments and its function is merely to pick up some adjustments in income-expenditure flows that are necessary to avoid leakages:

$$(1-t_{IT}^{CP})r\bar{K}_{CP}+\sum_{a\in A}\overline{NT_{CP}^{a}}=P_I S_{CP} \qquad \text{(A.4)}$$

where:

$t_{IT}^{CP}$ Corporations' income tax rate

$r\bar{K}_{CP}$ The Value of Fixed Capital Services Endowment by Corporations

$\sum_{a\in A}\overline{NT_{CP}^{a}}$ Firms' Net Income Distribution Operations

among Agents, $a \in A = CP, H, G, XM$

$P_I S_C$ Value of Corporations' Savings, i.e. Non-distributed surplus

***Households: Calibration of a Linear Expenditure System.***

Consumption, *C*, and Saving, *S*, activities of a representative household are characterised using a Cobb-Douglas utility function:

$$U(C,S_H)=C^{\alpha}\,S_H^{(1-\alpha)} \qquad \text{(A.5)}$$

Under this assumption, consumption, *C*, and household savings, $S_H$, of the representative utility maximising household represents constant shares over disposable income. Total consumer's income comes from labour, capital revenues and overall transfers, i.e. social transfers, other transfers, and property income transfers. From the after income tax or net income ($m_n$) other transfers are deducted since they are not subject to taxation.

Consumption behaviour proper is represented here with a linear expenditure system (LES):

$$U_c=\Pi(C_i-c_i)^{\delta_i} \qquad i=1.....N \qquad \text{(A.6)}$$

where $C_i$ refers to total quantity consumed of the *i-th* commodity and $c_i$ denotes the "subsistence" consumption. Thus, according to (A.6) consumption activities will contribute by the weight $\delta_i$ positively to utility levels, as far as the basic needs had been fulfilled. Solving the problem of a utility-maximising consumer, the optimal quantity demanded for the *i-th* commodity is characterised by:

$$C_i = \bar{c}_i + \frac{\delta_i}{P_i}\left(\alpha m_n - \sum_{j=1}^{N} P_j c_j\right) \quad \text{(A.7)}$$

$m_n$ refers to the after tax or net income while $\alpha m_n$ denotes that proportion devoted to consumption activities. The taxes charged on household gross income include labour and income taxes. Gross income ($m$) is composed by:

- $w_n(1-u)\bar{L} + r_n \overline{K}_H$: Factor rents: rents from that part of labour supply hired in the economy and capital supplied by households where $w_n$, $r_n$, $u$ and $\bar{L}$ denote respectively unitary after tax labour and capital rents, the unemployment rate and the total labour endowment in the economy.

$NTH^{CPI}$: Net transfers to households deflated by the *CPI*, i.e. consumer price index, variations

- $b_u w_n \bar{L} u$: Total unemployment subsidy, which is a margin over net wages.

Then:

$$m = w_n(1-u)\bar{L} + r_n \overline{K}_H + NTH^{CPI} + b_u w_n \bar{L} u \quad \text{(A.8)}$$

***Government***

The government collects taxes from consumption, production and income generation. This tax revenue ($T$) together with the income generated from capital endowments ($r_n \overline{K}_G$) and other received transfers ($TG$) allow the public sector to buy goods for public consumption in fixed proportions ($GC$), carry on investment activities ($GI$) and undertake transfer operations to other agents in the economy ($GT$). All inflow $TG$ and outflow $GT$ governmental transfers are deflated by the CPI variations. Their difference constitutes net transfers to the government $NTG$. Thus the amount of government's savings ($S_G$) is endogenous in this model representing government deficit or surplus. The government deficit ($GD$) or surplus is then defined as:

$$S_G = GD = T + NTG_{CPI} - GC - GI \qquad \text{(A.9)}$$

***Foreign Sector and Macroeconomic Closure Rule***

Since Spain is an open economy, the trade balance might be positive (surplus) or negative (deficit). Furthermore, macroeconomic consistency rules establish that the trade balance between our economy and the foreign economies has to be translated into foreign sectors' savings ( $S_{XM}$ ), which is a component of total savings.

$$S_{XM} = P_X (X_M - \overline{E}x) + NTX_{P_x} \qquad \text{(A.10)}$$

As indicated in expression (A.10), foreign sectors' savings corresponds to the difference between total imports and total exports $(\overline{E}x)$ in value terms plus the deflated net transfers to the foreign sector $(NTX_{Px})$. Exports in our model are not price sensitive. The price of the trade balance $(P_x)$ is a price index that refers to a weighted average of exports valued at final gross prices:

$$P_x = \sum_{i=1}^{N} cEx_i P_i^G \qquad \text{(A.11)}$$

where $cEx_i$ refers to the commodity share over total exports.

The model's macroeconomic closure rule refers then to the balance between investment and savings. Total investment is determined by all economic agents' savings and is given by:

$$S = I = S_{CP} + S_H + S_G + S_{XM} \qquad \text{(A.12)}$$

Therefore total investment in the economy ($I$ ) is the sum of overall agents' savings ($S$). As usually done in CGE models, a Leontief technology with fixed coefficients $cIv$

describes the allocation of total investment to sectoral final demand. As in the case of the trade balance, its price, $P_I$, is a weighted average of commodities final gross prices, $P$ :

$$P_I = \sum_{i=1}^{N} cIv_i P_i \tag{A.13}$$

***Equilibrium Conditions***

The circular flow of income constitutes the conceptual foundation of any coherent general equilibrium model. Within this circular flow of income, households and firms play a relevant role. Households are the owners of the factors of production and are final consumers of those commodities produced in the economy. Firms hire factors of production from households to produce commodities that households consume. In the structure of our CGE model, we explicitly represent government behaviour. However, most often the role of the government in the circular flow of income is passive. As mentioned in Section 5.3.4 above, the government collects taxes and distributes part of these revenues to the remaining economic agents as subsidies and lump-sum transfers. The other part of the governmental income is used to undertake public investment and finance public consumption.

Equilibrium in the economic flows results in the conservation of both product and value. Neither product nor value can appear from nowhere or disappear from the economic system. Product and value resources must equal their uses. These accounting rules constitute the core of Walrasian general equilibrium.

In our model, the Walrasian equilibrium is described by a vector of prices for the $N$ commodities and production factors prices $(P_i^*, w^*, r^*)$, a vector of total production outputs $X^*$, a level of gross capital formation $I^*$, public deficit $S_G{}^*$, unemployment rate $u^*$ and a level of tax revenues $RT^*$ that fulfil the following equilibrium conditions:

i) Market for commodities clear: For a given commodity the quantity produced must equal the sum of the quantities demanded in the economy.

$$X^* = AX^* + C(P^*, w^*, r^*, u^*) + I^* + GC^* + NEx \tag{A.14}$$

where $AX^*$ is intermediate demand and $NEx$ refers to net exports.

ii) The market for capital clears. In this sense the capital quantities demanded by firms must exhaust the aggregate supply of capital endowed to the economic agents. The case of labour is the exception. In this market, the quantities demanded by firms must equal total labour supply that is being used and may not correspond to total labour endowment:

$$\begin{aligned} \bar{K} &= Kd(w^*, r^*, X^*) \\ \bar{L}(1-u^*) &= Ld(w^*, r^*, X^*) \end{aligned} \tag{A.15}$$

Where *Kd* and *Ld* refer to the conditional capital and labour demands.

iii) Total tax revenues coincide with total tax payments (*TP*):

$$T = TP(P^*, w^*, r^*, u^*, X^*) \tag{A.16}$$

iv) Total investment equal savings by all agents:

$$S = I = S_{CP} + S_H + S_G + S_{XM} \tag{A.17}$$

Equilibrium conditions i)-iv) refer to the product conservation principle. The last condition, condition v), relates however to the value conservation principle.

v) The final price of each commodity in the economy must equal the sum of the values of all the inputs used to produce it. The value conservation principle simultaneously reflects the constant-returns-to-scale assumption and perfect competitive markets. Thus in equilibrium producers make zero profits:

$$\prod_i (P^*, r^*, w^*) = R_i(P^*, r^*, w^*) - C_i(P^*, r^*, w^*) \leq 0 \quad \forall i \qquad \text{(A.18)}$$

This implies that for each commodity produced in the economy the unit profit function, which is the difference between the unit cost function and the unit revenue function, must be equal or higher than zero.

Because of Walras' Law, we need to select a *numéraire* to solve the system. The selected price is labour's net rental price.

There is a direct "technological" link between the level of economic activity and the level of emissions. The emission technology follows a Leontief function form where emissions levels in tones per unit of output are fixed. We only consider $CO_2$ emissions generated in domestic production activities and in domestic final demand ruling out in this last case any exported emissions (through any energy exports). In fact this by-product from economic activity, represent almost 98 percent over total pollutant emissions levels.

***Data and Model Calibration***

In order to evaluate the possible rebound effects of energy efficiency policies in the context of the Spanish economy, we use a multi-sectoral static applied general equilibrium model for an open and small economy such as the Spanish one. Our model is calibrated on a Social Accounting Matrix for the base year of 2004 constructed specifically for this work. All prices are considered as index numbers with a value equal to unity in the benchmark equilibrium. All value flows in the SAM used in this analysis are also treated as benchmark quantities. These two assumptions make possible to obtain the technical coefficients and some of the elasticity parameters of the utility and production functions directly from the SAM data. In the calibration of the model, we have included initial tax rates following the methodology proposed by Sancho (2009).

The additional information used to calibrate the model refers to previous econometric analysis. Firstly, in the production side, estimates of the short-run

Armington elasticities of substitution in expression (A.1), denoted by $1/(1-\rho)$, correspond to the average values over all European members taken from previous empirical analysis (Hertel, 1997, Németh *et al*, 2008). According to the latter analysis, short-run elasticities for energy inputs are around 1.68 while for non-energy sectors are on average 0.9 thus very close to a Cobb-Douglas technology. When calibrating domestic production, the Hicks elasticity of substitution considered between *K* and *L*, i.e. $\sigma_{KL}$ in expression (A.2) is set to 1.26 and it has been also taken from previous empirical studies (Hertel, 1997) and made equal in all sectors.

In calibrating the wage curve presented in (A.3), the value of $\beta$ equals -0.13 and is an average estimated elasticity for the case of Spain (Sanromà and Ramos, 2003)

Secondly, in the consumers' side, differently to the Cobb-Douglas and CES utility functions, which are the most widely-used forms in CGE modelling, the LES structure allows the income elasticity of demand to vary across commodities. These income elasticities for the consumption of the *N* commodities are based upon the empirical estimates in Theil *et al*. (1989) (See Table A.2 in the Annex). These estimates were adjusted to fulfil the Engel aggregation property. However, another parameter needs to be known in order to correctly calibrate "subsistence" quantities, $c_i$. This parameter is the Frisch parameter (1959) which is the expenditure elasticity of the marginal utility of expenditure:

$$\varphi = -\frac{\alpha m_n}{\alpha m_n - \sum_{i=1}^{N} P_i^G \bar{c}_i} \qquad \text{(A.19)}$$

The estimate of the Frisch parameter $\varphi$ is based upon the analysis made by Lluch *et al* (1977) for the European Union and is set equal to -2.07.

## ANNEX

*Table AP.1.Sectorial breakdown for Spanish I/O 04 Data*

| *Sectors Code* | *Classification* | *Sectors* | *NACE-93 code* |
|---|---|---|---|
| **E1** | *Energy Sectors* | *Extraction of Anthracite, Coal, Lignite and Peat* | **10** |
| **E2** | | *Extraction of Crude, Natural Gas, Uranium and Thorium* | **11-12** |
| **E3** | | *Coke, Refinery and Nuclear fuels* | **23** |
| **E4** | | *Production and Distribution of Electricity* | **401** |
| **E5** | | *Production and Distribution of Gas* | **402-403** |
| **I1** | *Non Energy Sectors* | *Primary Sector* | **01, 02, 05** |
| **I2** | | *Other Extraction Industries* | **13-14** |
| **I3** | | *Water Sector* | **41** |
| **I4** | | *Food, Beverage, Tobacco, Textile and Leather Products* | **151-152, 154-155, 156-159, 16-19** |
| **I5** | | *Other Industrial Sectors & Recycling* | **20-22,37** |
| **I6** | | *Chemistry Industry, Rubber and Plastic Industry* | **24-25** |
| **I7** | | *Manufacturer Industry: Minerals, Furniture, Metallic Products, Equipment & Electronic Products.* | **261-268, 27-36** |
| **I8** | | *Construction* | **45** |
| **I9** | | *Commercial & Transport Activities* | **50-52, 61-62, 601-603, 63.1-63.2, 63.4** |
| **I10** | | *Market Services* | **65-67, 70-72, 74, 80, 85, 90, 92, 93, 63.3** |
| **I11** | | *Non Market Servicies & Public administration* | **75, 80, 85, 90, 92** |

*Table AP.2: Estimates for Income Elasticities.*

| *Sectors* | *Income Elasticities* |
|---|---|
| ***Extraction of Anthracite, Coal, Lignite and Peat*** | **0.09** |
| ***Extraction of Crude, Natural Gas, Uranium and Thorium*** | **0** |
| ***Coke, Refinery and Nuclear fuels*** | **1.2** |
| ***Production and Distribution of Electricity*** | **1.2** |
| ***Production and Distribution of Gas*** | **1.2** |
| ***Primary Sector*** | **0.1** |
| ***Other Extraction Industries*** | **0.1** |
| ***Water Sector*** | **0.4** |
| ***Food, Beverage, Tobacco, Textile and Leather Products*** | **0.55** |
| ***Other Industrial Sectors & Recycling*** | **1.4** |
| ***Chemistry Industry, Rubber and Plastic Industry*** | **1.4** |
| ***Manufacturer Industry: Minerals, Furniture, Metallic Products, Equipment & Electronic Products.*** | **1.5** |