RETHINKING ECONOMY-WIDE REBOUND MEASURES:

AN UNBIASED PROPOSAL

Ana-Isabel Guerra
Department of Applied Economics
Universitat Autònoma de Barcelona
aigh79@gmail.com

Ferran Sancho
Department of Economics
Universitat Autònoma de Barcelona
ferran.sancho@uab.cat

May 2010

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.

Keywords: Rebound effect; Rebound evaluation; Energy efficiency.

JEL Classification: C63, C68, D58, Q55

---

[1]Support from research grants MICINN-ECO2009-11857 and SGR2009-578 is gratefully acknowledged.
Corresponding author: Ferran Sancho, email: Ferran.sancho@uab.cat

1. Introduction: to Rebound or not to Rebound, still an open question

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 of the 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 (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 is 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, changes in the effective price of energy 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, which turns out to play a determining role in measuring the rebound impacts (Saunders, 1992). 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,* 1999). We first make a distinction between energy in natural units, E, measured by kWh or PJ [2], and energy in effective or efficiency units, ε, 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 τ that represents "human ideas", in other words, technology:

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

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 Z percent improvement in energy efficiency, i.e. a positive change in τ, without any change in physical quantities, the effective energy use will be Z 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

[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 (2008) for a more detailed description of the possible definitions of rebound and its implications.

[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.

analysis is the fact that, provided the price of energy in physical units (P_E) remains constant, any change in energy efficiency will have a corresponding impact on the effective price of energy (P_ε), when measured in efficiency units. Specifically:

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

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:

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

where η_ε^τ is the efficiency elasticity of the 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:

$$\frac{dE}{E} = (\eta_\varepsilon^\tau - 1)\frac{d\tau}{\tau} \quad \text{and then} \quad \eta_E^\tau = (\eta_\varepsilon^\tau - 1) \tag{5}$$

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

$$R = \left(1 + \eta_E^\tau\right) \cdot 100 \tag{6}$$

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:

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

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.

Elasticity of Energy in Effective Units	Rebound Effect	Implication for Potential Energy Savings
Perfectly inelastic $\eta_{\varepsilon}^{\tau}=0$	*Zero Rebound* R=0%	*Potential Energy Savings are wholly preserved:* $\frac{dE}{E}=-\frac{d\tau}{\tau}$
Inelastic $0<\eta_{\varepsilon}^{\tau}<1$	*Positive Rebound* *0* <R<100%	*Potential Energy Savings are partially preserved:* $\frac{dE}{E}<0$ *but* $\left\|\frac{dE}{E}\right\|>\left\|\frac{d\tau}{\tau}\right\|$
Elastic $\eta_{\varepsilon}^{\tau}>1$	*Backfire effect* R>100%	*The energy efficiency improvement leads to an increase in the demand for energy in natural units. Potential Energy Savings completely lost:* $\frac{dE}{E}>0$

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 Z percent, potential energy savings would correspond to that Z 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:

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

Here E_i, τ_i, $\overline{P}$ and $\overline{X}$ denote, respectively, sectoral energy input demand, energy efficiency gains, a market price vector, and the market quantity vector excluding the energy sector where efficiency improvements occur. N in turn indicates 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 rather be 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 these 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:

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

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 minus 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}):

$$R^b = \left[1 - \frac{AES^{GE}}{PES^{PE}}\right] \cdot 100 \qquad (11)$$

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:

$$R^u = \left[1 - \frac{AES^{GE}}{PES^{GE}}\right] \cdot 100 \tag{12}$$

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 Leontief's 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, i.e. $a_{ij} = [A]_{ij}$ and final demand flows contained in a column vector f.

$$X_i = \sum_{j=1}^{N} a_{ij} X_j + f_i \quad \forall i, j \in N \quad \text{and} \quad f_i = [f]_i \tag{13}$$

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 non-negative 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 $d\tau / \tau$ in those technical coefficients that relate to the intermediate use of inputs coming from the energy sector (E) while the other coefficients remain constant. For simplicity, we assume that efficiency improvements are identical in all energy inputs. The new equilibrium in the Leontief's quantity model reads as:

$$X_i^{'} = \sum_{i=1}^{N} \left(1 - {d\tau}/{\tau}\right) \cdot a_{ij} \cdot X_j^{'} + f_j \quad \text{where} \quad \begin{cases} d\tau > 0 & \text{if } E = i \\ d\tau = 0 & \text{if } E \neq i \end{cases} \tag{14}$$

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

$$PES^{GE} = \frac{dX_E}{X_E} = \left(\frac{X_E^{'} - X_E}{X_E} \right) \tag{15}$$

***Table 2**: Potential General Equilibrium Savings from the Spanish SIOC-04 for 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 $\left|PES^{GE}\right| > \left|PES^{PE}\right|$ 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

The details of the CGE modelling approach, background data and calibrated elasticities for Spain in 2004 are described in the Appendix.

The energy efficient shock introduced in the CGE approach to evaluate actual energy savings under general equilibrium conditions (AES^{GE}) is carried out by increasing the benchmark productivity of the energy composite, i.e. benchmark effective energy composite, by 5 percentage points in the production structure presented in expression A.2 in the Appendix:

$$\frac{d\left(\tau \cdot E\right)}{\bar{\tau} \cdot \bar{E}} = \frac{d\tau}{\bar{\tau}} = 5\% \quad \text{with} \quad \frac{dE}{\bar{E}} = 0 \tag{16}$$

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.

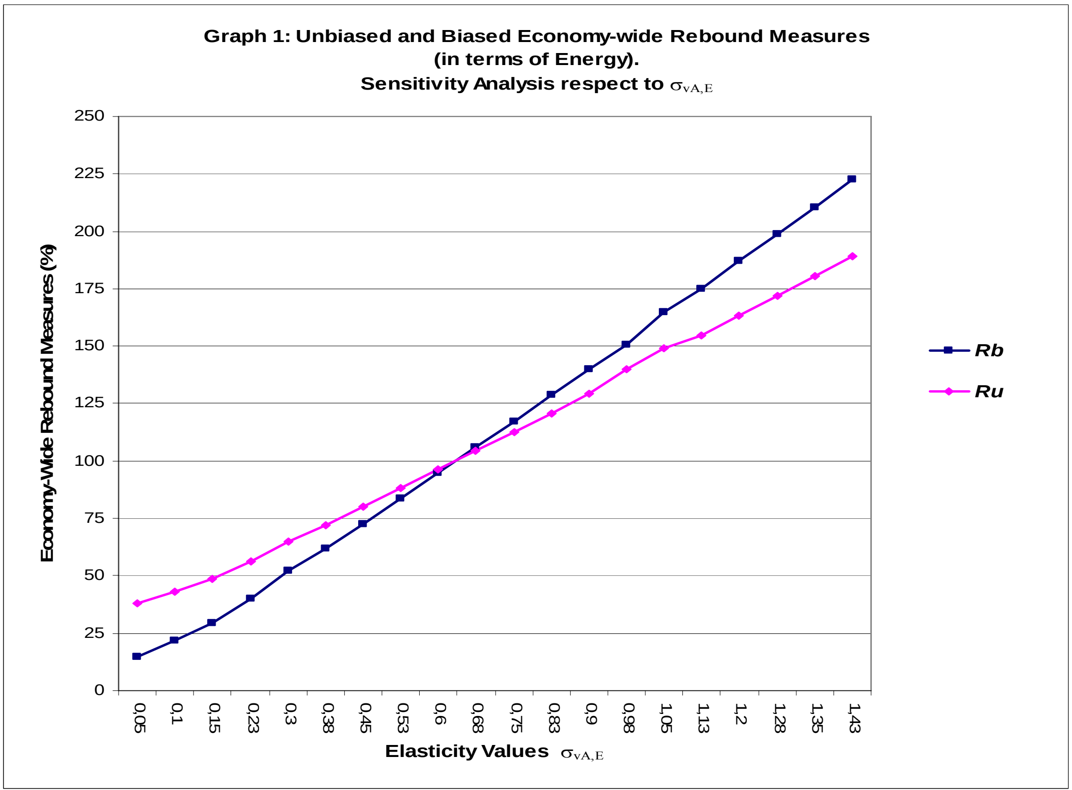
[3] Incorporating cost considerations when introducing an energy efficiency improvement will affect the nature and size of rebound effects (see Allan et al, 2007; Sorrel, 2007), as will the precise nature of its introduction. Here, in the first instance, the analysis is simplified by focussing on an 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 carried out a systematic sensitivity analysis varying in our simulations the elasticity of substitution between value-added and energy, $\sigma_{VA,E}$, homogenously in each sector. The results related to both rebound measures, the biased rebound measure and our unbiased proposal in energy and in CO_2 emissions terms are depicted respectively in Graphs 1 and 2. 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; 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.* $\sigma_{M,VAE}$.

We can see from Graphs 1 and 2 that the higher the elasticity of substitution between value-added and energy, the larger the proportion of potential energy savings that are eroded due to price mechanisms. As was pointed out by previous empirical research (Allan *et al*, 2007, and Turner, 2008) the rebound effect increases with the degree of concavity of the isoquants. Furthermore, the value of the elasticity of substitution between energy and value-added, i.e. the upper nest elasticity, also determines both the size and sign of the bias when potential energy savings are inappropriately quantified under partial equilibrium conditions. Notice that when economy-wide rebound impacts are lower than 100 percent, i.e. positive economy-wide rebound impacts, the evaluated unbiased economy-wide rebound effects is above the biased measure. This indicates that using expression (11) instead of expression (12) to compute rebound impacts under general equilibrium conditions leads to downward bias in this measure. When there is a positive economy-wide rebound effect, the higher the upper nest elasticity, the lower the distance $R^u - R^b$ and, consequently, the bias. This relationship between the elasticity of substitution and the economy-wide rebound bias reverses when backfire effects occur, i.e. when economy-wide rebound effects are larger than 100 percent. Under this scenario, the biased economy-wide rebound measure is above the unbiased one implying an upward bias of backfire effects. This empirical exercise therefore reinforces the conclusions already drawn in section 2.2.


Graph 1: Unbiased and Biased Economy-wide Rebound Measures
(in terms of Energy).
Sensitivity Analysis respect to $\sigma_{vA,E}$
Economy-Wide Rebound Measures (%)
0 25 50 75 100 125 150 175 200 225 250
0,05 0,1 0,15 0,23 0,3 0,38 0,45 0,53 0,6 0,68 0,75 0,83 0,9 0,98 1,05 1,13 1,2 1,28 1,35 1,43
Elasticity Values $\sigma_{vA,E}$
Rb
Ru

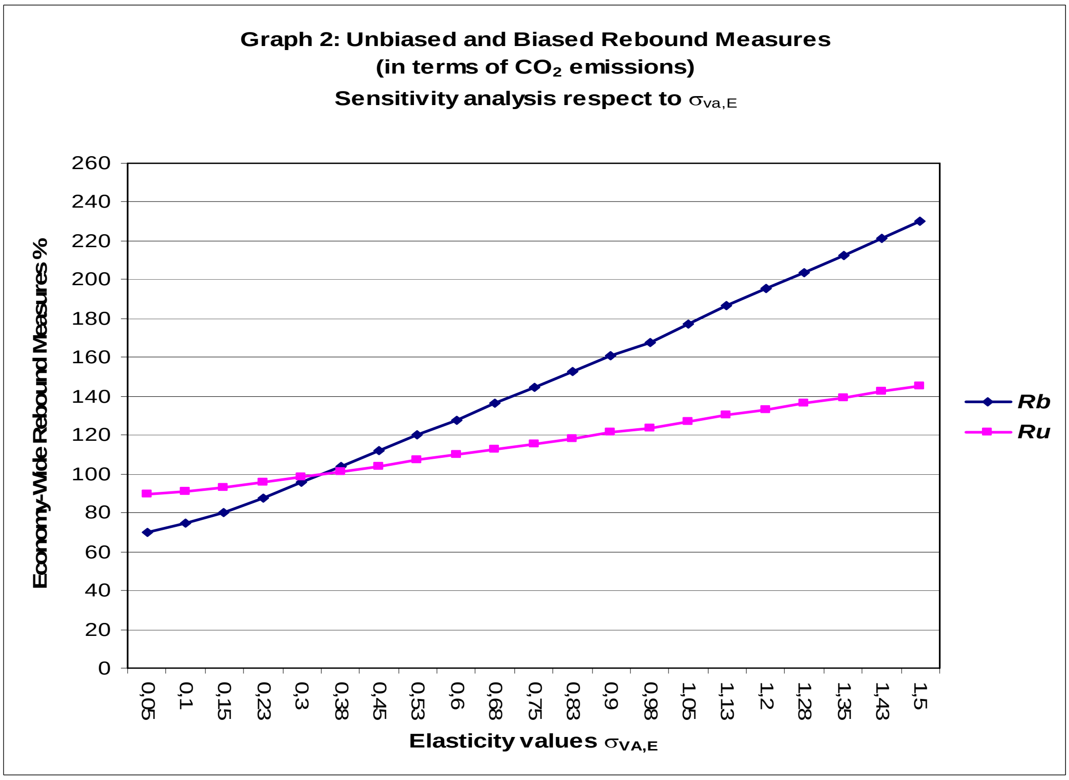
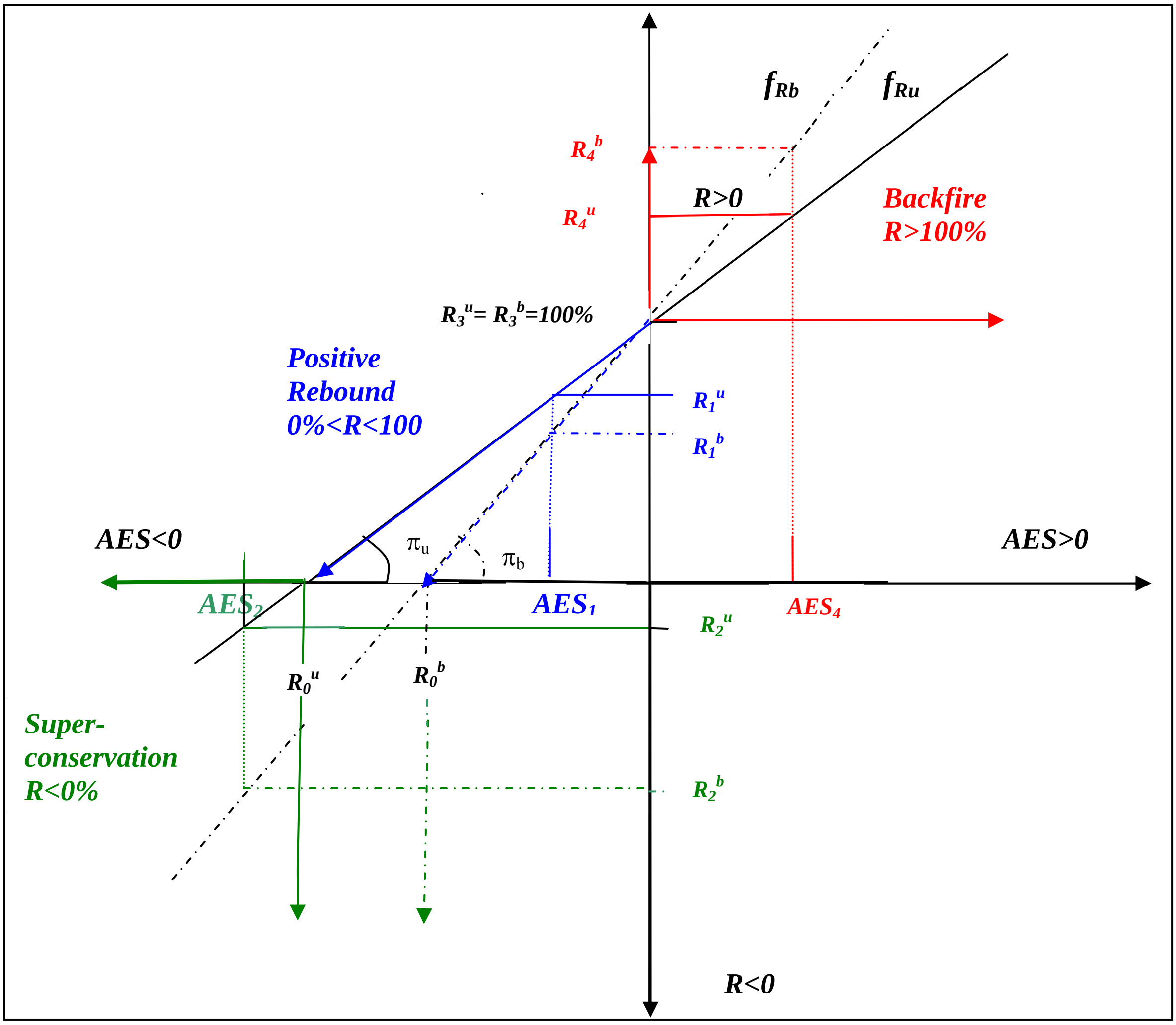

Graph 2: Unbiased and Biased Rebound Measures
(in terms of CO_2 emissions)
Sensitivity analysis respect to $\sigma_{va,E}$
Economy-Wide Rebound Measures %
0 20 40 60 80 100 120 140 160 180 200 220 240 260
0,05 0,1 0,15 0,23 0,3 0,38 0,45 0,53 0,6 0,68 0,75 0,83 0,9 0,98 1,05 1,13 1,2 1,28 1,35 1,43 1,5
Elasticity values $\sigma_{VA,E}$
Rb
Ru

Table 3: Rebound Measures in terms of energy and $C0_2$ emissions savings. Simulated costless-exogenous $d\tau / \tau = 5\%$. Leontief, Cobb-Douglas and Elastic upper bound elasticities.

Rebound Measures and Distance	***Benchmark Elasticity Values*** $\sigma^i_{VA,E}$		**Case1:** $\sigma^i_{VA,E} \approx 0$		**Case 2:** $\sigma^i_{VA,E} \approx 1$		**Case 3:** $\sigma^i_{VA,E} = 1.5$	
	E	***$C0_2$***	**E**	***$C0_2$***	**E**	***$C0_2$***	**E**	***$C0_2$***
R^u	*90.81*	*108.07*	*38.04*	*89.41*	*126.99*	*152.43*	*145.48*	*198.15*
R^b	*87.38*	*123.13*	*14.91*	*69.68*	*177.32*	*172.00*	*230.28*	*234.80*
$(R^u - R^b)$	*3.43*	*-15.06*	*23.14*	*19.73*	*-50.33*	*-19.57*	*-84.80*	*-36.65*

Table 3 summarises the evaluated economy-wide rebound impacts, in both energy and CO_2 emissions terms, obtained through the sensitivity analysis mentioned above. We have included the results for the "benchmark" elasticities (see the Appendix) along with three familiar cases: a Leontief scenario whereby the upper nest elasticity is close to zero, i.e. $\sigma^i_{VA,E} \approx 0$, a Cobb-Douglas case, i.e. $\sigma^i_{VA,E} \approx 1$, and an "elastic" scenario with $\sigma^i_{VA,E} = 1.5$. Two main conclusions can be drawn from the results included in Table 3. The first one relates to the potential economy-wide rebound impacts that might be generated in the Spanish economy. According to our findings, a 5 percent exogenous increase in energy efficiency might lead to positive economy-wide rebound effect in energy terms close to a backfire scenario whereby all potential energy savings are effectively lost. The second conclusion refers to the size of the rebound effect when the elasticity of substitution is close to zero. In this scenario, the economy-wide rebound effect, though lower than under the benchmark case, is still positive and close to 40 percent. This result reinforces the conclusions of Turner (2009). This author stresses the relevance of measuring rebound impacts under a general equilibrium approach for this allow us to consider other parameters, such as the Armington elasticities, that in an indirect way have also an effect for the presence and size of rebound impacts.

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



We illustrate the reasoning behind the potential sign of the economy-wide bias in Figure 1. 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. π_b and π_u. Notice that since $|PES^{GE}| > |PES^{PE}|$ then $|\pi_b| > |\pi_u|$. These two linear functions are therefore defined as:

$$f_{R^b} = (1 - \pi_b \cdot AES) \cdot 100$$
$$f_{R^u} = (1 - \pi_u \cdot AES) \cdot 100 \qquad (17)$$

As can be seen from Figure 1, and 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 with 0<*R*<100 percent, using expression (11) instead of (12) would lead to a downward bias of economy-wide rebound effects. This is AES_1 in Figure 1 where $R_1^u > R_1^b$. When *PES* <*AES*<0 and *R*>100 percent, this indicates a super-conservation scenario. In this case, if *PES* are measured under partial equilibrium conditions, this practice 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 $R_4^b > R_4^u$. 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 elasticities. 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.

5. Conclusions

The main target of this paper is to propose 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 offsetting efficiency improvements. They reflect the wedge between actual energy savings, which account for these price effects, and potential energy savings. The methodological message is that to avoid bias in measuring economy-wide rebound effects both potential and actual energy savings should be evaluated under general equilibrium conditions.

Previous analyses, in contrast, have quantified actual and potential energy savings under different equilibrium scenarios. 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 us to compute 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, on the other hand, provides information about the actual energy savings under general equilibrium conditions because the effects of prices and quantities are simultaneously accounted for.

We have formally defined the source of bias in economy-wide rebound effects measures and have proposed a way to correct this bias. In addition, we have also carried out an empirical exercise for the Spanish economy as an illustration. 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.

Bibliography

Allan, G., Hanley N., McGregor, P.G., Swales, K., Turner, K., 2007. The macroeconomic rebound effect and the UK economy. Final report to the Department Of Environment Food and Rural.

Armington, P., 1969. A theory of demand for products distinguished by place of production. IMF Staff Papers, 16, pp. 157-178.

Binswanger, M., 2001. Technological Progress and Sustainable Development: what about the Rebound?. Ecological Economics, 36, pp. 119-132.

Berkhout, P.H.G., Muskens, J.C., Velthuijsen, J.W., 2000. Defining the Rebound Effect. Energy Policy, 28, pp. 425-432.

Blanchflower, D.G., Oswald, A.J., 1990. The Wage Curve. Scandinavian Journal of Economics, 92, pp. 214-235.

Blanchflower, D.G., Oswald, A.J., 1994. The Wage Curve. M.I.T. Press, Cambridge, Massachusetts.

Brookes, L. G., 1990. The Greenhouse Effect: the Fallacies in the Energy Efficiency Solution. Energy Policy, 18, pp. 199-201.

Böhringer, C., Ferris, M., Rutherford, T., 1997. Alternative CO2 Abatement Strategies for the European Union, in Proost, S. and Brader, J. (eds) Climate Change, Transport and Environmental Policy. Edward Edgar, Cheltenham.

Frisch, R., 1959. A Complete Scheme For Computing All Direct And Cross Demand Elasticities in a Model With Many Sectors. Econometrica 27, pp. 177-196

Frondel, M., Schmidt, C.M., 2005. Evaluating environmental programs: the perspective of modern evaluation research. Ecological Economics 55, pp. 515–526.

Greene, D. L., Kahn, J.R, Gibson, R.C., 1999. Fuel economy rebound effect for US household vehicle. Energy Journal, 20, pp. 1-31.

Greening, L. A., Greene, D.L., Difiglio, C., 2000. Energy efficiency and consumption – the rebound effect – a survey. Energy Policy, 28, pp. 389-401.

Hertel, T. W. (ed.), 1997. Global Trade Analysis. Modeling and Aplications. Cambridge University Press, Cambridge.

Jevons, W.S., 1865. The Coal Question. Macmillan, London. Economic Growth and Income Inequality, 1955, American Economic Review, 45, pp. 1 -28.

Khazzoom, J. D., 1980. Economic implications of mandated efficiency in standards for household appliances. Energy Journal, 1, pp. 21-40.

Leontief, W.W., 1941. The Structure of the American Economy. Oxford University Press, New York.

Lluch, C., Powell, A., Williams, R.A., 1977. Patterns in household demand and savings. Oxford University Press, Oxford.

Mansur, A., Whalley, J., 1984. Numerical specification of applied general equilibrium models: estimation, calibration and data. In Scarf, H., Shoven, J. (eds.): Applied General Equilibrium Analysis, Cambridge University Press, New York.

Németh,G., Szabó, L., Ciscar, J.C., 2008. Estimation of Armington Elasticities in an Energy CGE model for Europe. Working paper of the Institutes of Prospective Technological Studies, Seville (Spain).

Sancho, F., 2009. Calibration of CES Functions for Real-World Multisectoral Modelling. Economic Systems Research, 21, pp. 45-58

Sanromá, E., Ramos, R. 2003. Wage Curves in Spain. Evidence from the Family Budget Survey. Working Papers in Economics, Number 101. Espai de Recerca en Economia, Universitat de Barcelona.

Saunders, H. D., 1992. The Khazzoom-Brookes postulate and neoclassical growth. The Energy Journal, 13, pp. 131-148.

Saunders, H. D., 2000(a). Does predicted rebound depend on distinguishing between energy and energy services?. Energy Policy, 28, pp. 497-500.

Saunders, H. D., 2000(b). A view from the macro side: rebound, backfire, and Khazzoom-Brookes. Energy Policy, 28, pp. 439-449.

Saunders, H. D., 2008. Fuel conserving (and using) production functions. Energy Economics, 30, pp. 2184-2235.

Scarf, H.E., 1967. On the Computation of Equilibrium Prices. In Fellner, W.J. (ed), Ten Economic Studies in the Tradition of Irving Fisher. John Wiley & Sons, New York.

Schipper, L., 2000. Editorial, Energy Policy, 28, pp. 6-7.

Schipper, L. and Grubb, M. 2000. On the rebound? Feedback between energy intensities and energy issues in IEA countries, 28, pp. 367-388.

Shoven, J.B., Whalley, J., 1984. Applied General Equilibrium Models of Taxation and Trade: An Introduction and Survey, Journal of Economic Literature, 22, 1007-1051.

Simon, J., 1981. The Ultimate Resource. Princeton University Press, Princeton.

Sorrell, S., 2007. The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency. A report produced by the

Sussex Energy Group for the Technology and Policy Assessment function of. The UK Energy Research Centre.

Sorrell, S., Dimitropoulos, J., 2008. The rebound effect: microeconomic definitions, limitations and extensions. Ecological Economics 65, pp. 636–649.

Theil, H., Cheng, C.F., Seale, J.L. Jr. 1989. International Evidence on Consumption Patterns, Greenwich, CT: JAI Press, Inc.

Turner, K., 2008. A computable general equilibrium analysis of the relative price sensitivity required to induce rebound effects in response to an improvement in energy efficiency in the UK economy, Strathclyde Discussion Papers in Economics, No. 08-07.

Turner, K., 2009. Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK economy. Energy Economics, 31. pp. 648-666.

Vega-Cervera, J.A., Median, J., 2000. Energy as a Productive Input: The Underlying Technology for Portugal and Spain. Energy, 25, pp. 757-775.

APPENDIX: The CGE model of the Spanish Economy

General description.

The model includes N=16 representative firms, 4 types of inputs in production, (capital, labour, energy and non-energy materials), a representative household, a government sector, an account for corporations, an external sector and a capital (savings/investment) account. Agents behave rationally and are profit and utility maximisers. No agent has significant market power.

Each representative firm minimizes costs subject to a constant-returns-to-scale technological constraint, thus profits turn out to be zero. Markets are assumed to be competitive. Production is articulated using nested constant elasticity of substitution (CES) functions. In the first level, gross output is obtained following an Armington (1969) assumption with imported products being imperfect substitutes for domestic production. In the next levels, domestic output results from combining the 4 production inputs (capital, labour, energy and materials) using a succession of nested CES functions. Each representative firm produces a single good. These 16 sectors and goods are classified into 5 energy (sectors 2-3, 5-7) and 11 non-energy materials sectors (1, 4, 8-16). See sectoral details in Table AP1 below. This distinguishes two relevant production blocks in the economy: the energy block and the non-energy block. Both blocks make use of a multi-level and sectors' homogenous technology.

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

The government supplies a public consumption good, supports public investment and carries out income transfers to private sectors. These activities are financed through taxes and, if necessary, incurring in a 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).

Corporations act 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. 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 possible exception of the labour market. Total supply of labour is fixed but is composed of two parts, one related to active labour being demanded by firms and another one 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. The closure rule guarantees that in equilibrium the aggregate equality between investment and savings holds.

The CGE model is implemented using a Social Accounting Matrix (SAM) of the Spanish economy for 2004. In the calibration all value flows are taken as benchmark quantities using the standard unit price normalization. Most model parameters can therefore be obtained from the reference SAM. To deal with the presence of taxes we use the methodology of Sancho (2009). The exogenous elasticities have been decided upon literature search.

Total Production.

Gross output X_i for the set of tradable goods T is a CES composite between domestic output X_i^D and imports X_i^M :

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

Thus there is imperfect substitution between domestic output and imports which is governed by an Armington elasticity $\sigma_i = 1/(1-\rho_i)$. We consider different Armington elasticities for the energy and non-energy block though homogenous within blocks. For non-tradable goods, total output coincides with domestic output.

Domestic Production: KLEM specification

Domestic production X_i^D is obtained using a CES *KLEM* (Capital *K*, Labour *L*, Energy *E*, and Materials *M*) nested production function:

$$\begin{aligned} VA_i &= \left(\delta_i (A_i^K K_i)^{\rho_{K,L}} + (1-\delta_i) \left(A_i^L L_i \right)^{\rho_{K,L}} \right)^{1/\rho_{K,L}} \\ VAE_i &= \left(\beta_i (\tau E_i)^{\rho_{VA,E}} + (1-\beta_i) VA_i^{\rho_{VA,E}} \right)^{1/\rho_{VA,E}} \\ X_i^D &= \left(\alpha_i (A_i^M M_i)^{\rho_{M,VAE}} + (1-\alpha_i) VAE_i^{\rho_{M,VAE}} \right)^{1/\rho_{M,VAE}} \end{aligned} \qquad \text{(A.2)}$$

Firstly, Value-Added *VA* is a composite of Labour and Capital. Secondly, Energy and Value-added yield a new composite *VAE,* which in turn is aggregated with Materials to produce domestic output. Factor efficiency is input specific and represented by A_i for each of the capital, labour and materials inputs and remains constant in the simulations. Energy efficiency gains take place in the energy composite and are reflected by the parameter τ . The materials and energy composites in (A.2) are obtained as Leontief fixed coefficients of the 11 non-energy and 5 energy goods, respectively. Future research will relax the latter assumption introducing imperfect substitution between primary and secondary energy inputs (Böhringer *et al*, 1997) and between renewables a non-renewables.

Non-produced inputs

The CGE model is a short-run model where the supply of capital is fixed but mobile among sectors. In the labour market, however, there is unused labour. We incorporate this feature using a wage curve (Blanchflower and Oswald, 1990, 1994) that reflects the relationship between real-wages ω / CPI and unemployment *u*. While the total endowment of labour is given and fixed its use in production activities is not. Thus unemployment is endogenous in the model. The specification of the wage curve is given by:

$$\frac{\omega}{CPI} = u^{\theta} \tag{A.3}$$

where θ is a parameter governing the relationship between the real wage and the unemployment rate.

Corporations

The Corporations' account in a SAM 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. In the model, this account plays a simple "book-keeping" role and its function is merely to pick up some adjustments in the income-expenditure flows:

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

In expression (A.4) t_{IT}^{CP} is the Corporations' income tax rate, $r\overline{K}_{CP}$ is the Value of their fixed capital services endowment, $\sum_{a \in A} \overline{NT_{CP}^{a}}$ represent the income distribution operations, and $P_I S_C$ is Corporations' Savings, i.e. the non-distributed surplus.

Households' demand: A Linear Expenditure System.

Households' demand comes from a two-stage decision process. In the first one, consumers assign disposable income m_H to aggregate consumption *C* and savings S_H using a Cobb-Douglas aggregator:

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

Consumption behaviour proper is represented by a linear expenditure system (LES) with utility function:

$$U_C=\Pi_{i=1}^{N}(C_i-\overline{c}_i)^{\delta_i} \tag{A.6}$$

C_i stands for consumption of good *i* whereas $\overline{c}_i$ denotes the minimum or "subsistence" consumption. Maximising the LES utility under the assigned income to consumption, αm_H, yields the LES demand system:

$$C_i=\overline{c}_i+\frac{\delta_i}{P_i}\left(\alpha m_H-\sum_{j=1}^{N}P_j\overline{c}_j\right) \tag{A.7}$$

Facing an income tax rate of t_H, disposable income turns out to be:

$$m_H=(1-t_H)\left(\omega(1-u)\overline{L}+r\overline{K}_H+NTH+b_u\omega\overline{L}u\right) \tag{A.8}$$

The first two terms are households' factor rents from selling labour and capital in the factors markets. The third term is net transfers to the household, and the fourth term represents unemployment benefits.

Government

The government collects taxes from consumption, production and income generation. This tax revenue *T* along with the income generated from the government capital endowment $r\overline{K}_G$ allow the public sector to buy goods for public consumption G_C, finance public investment G_I and undertake net transfer operations with other agents in the economy G_{NT}. Thus government's savings S_G is endogenous and equal to its deficit G_D (or surplus, if positive):

$$S_G=G_D=T+rK_G-G_{NT}-G_C-G_I \tag{A.9}$$

Foreign Sector and Macroeconomic Closure Rule

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

$$S_{XM}=P_X(X^M-\overline{E}^X)+NTX(P_X) \tag{A.10}$$

The external sector's savings corresponds to the difference between total imports X^M and total exports $\overline{E}^X$, in value terms, plus deflated net transfers from the foreign sector $NTX(P_X)$. The price of the trade balance P_X is a price index that refers to a weighted average of traded goods valued at final gross prices.

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:

$$S = I = S_{CP} + S_H + S_G + S_{XM} \tag{A.11}$$

Total investment is sectorally distributed, in turn, using a fixed coefficient technology.

Equilibrium

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 the Walrasian general equilibrium concept.

In our model, equilibrium is described by a vector of prices P^* for the N commodities, factors' prices (ω^*, r^*), a vector X^* of total output, a level of gross capital formation I^*, a level of public deficit S_G^*, unemployment rate u^*, and a level of tax revenues T^* that fulfil the following equilibrium conditions:

i) Markets for all goods clear: Total equilibrium output is fully used in intermediate demand, households' demand, gross capital formation, public demand and net exports:

$$X^* = AX^* + C(P^*, \omega^*, r^*, u^*) + I^* + G_C + \overline{E}^X$$

ii) The market for capital clears. The market for labour may not clear but demanded labour is equal to adjusted labour endowment by unemployment:

$$\overline{K} = K^d(\omega^*, r^*, X^*)$$
$$\overline{L}(1 - u^*) = L^d(\omega^*, r^*, X^*)$$

iii) Total tax revenues T^* coincide with total tax payments TP by all agents facing direct and indirect taxes: $T^* = TP(\omega^*, r^*, u^*, X^*)$. Tax payments depend upon the different tax bases, which are endogenously determined.

iv) Total investment equals total savings: $I^* = S_{CP} + S_H + S_G + S_{XM}$

Equilibrium conditions i)-iv) refer to the product conservation principle. The last condition, condition v), relates 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 and prices coincide with average costs.

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

Emissions of CO_2

There is a direct "technological" link between the level of economic activity and the level of carbon dioxide emissions. The emissions 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.

Exogenous elasticities

Calibration from the SAM requires the adoption of some exogenous elasticity values. We borrow these values from econometrics studies. The Armington elasticities in are average values over all European members taken from Hertel (1997) and Németh et al (2008). Elasticity values for energy goods are closed to 1.7 while for non-energy goods the average value is 0.9, thus very close to a Cobb-Douglas elasticity. The substitution elasticity for Labour and Capital is set to 1.26 and taken from Hertel (1997). The calibration of the wage curve uses a value of $\beta = -0.13$ as reported for Spain in Sanromà and Ramos (2003). On the consumption side, the income elasticities in the LES subsytem are based upon the estimates in Theil *et al* (1989). The also needed Frisch (1959) parameter in the demand subsystem is adopted from the estimates by Lluch *et al* (1977) for the European Union and set equal to -2.07. More data details are available upon request.

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 Extractive Industries	13-14
I3		Water Sector	41
I4		Food, Beverage, Tobacco, Textile and Leather	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		Manufactures: Minerals, Furniture, Metallics & 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