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THE INFLUENCE OF ENERGY EFFICIENCY ON OTHER NATURAL RESOURCES USE: AN INPUT-OUTPUT PERSPECTIVE

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Abstract

Energy efficiency improvements reduce the costs of energy services, and under some circumstances, increase the available income. This generates an additional increase of consumption of goods and services that need additional energy to be produced, distributed and consumed. This effect is known as the indirect rebound effect in the literature. However, beyond this additional increase of global energy consumption, there is also a variation of the use of other natural resources due to the same mechanism. This effect, which we label as direct and indirect cross rebound effect, is generally not considered by academia nor policy-making when designing and implementing energy policies. This research conceptualizes this effect, develops a methodology for its estimation and provides estimates for the Spanish economy. Results show that an energy efficiency in households could increase the use of minerals and water, while reducing the use of energy, fossil fuels and metal ores in Spain. These reductions, however, are lower than the expected ones from an input-output perspective, leading to positive direct and indirect cross rebound effects: between 64.6%-74.7% for energy (equivalent to direct and indirect rebound effect); 48%-63% for fossil fuels. 84%-89% for metal ores; backfire for non-metallic minerals (147%-134%) and extreme backfire for water (1,191%-1,628%).

Keywords: energy efficiency, cross rebound effect, environmental rebound effect, resource use, input-output.

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1. Introduction

1.1. Background and motivation

Energy efficiency improvements are often promoted to reduce energy consumption from different economic agents, such as households, industries and governments. Such improvements are applied to various areas, such as lighting, heating, cooling, industrial processes, and other areas that require energy. It is one of the most widespread policies to deal with energy dependency and environmental problems in most countries (IEA 2015). Increasing concerns on climate change have also fostered these policies in order to reduce global carbon emissions and tackle global warming.

There is, however, a known controversy among energy economists. Energy efficiency improvements can be totally or partially offset by the so-called rebound effect. This effect has been widely studied for energy uses (Brookes, 1979; Khazzoom, 1980; Saunders, 1992; Greening et al., 2000; Sorrell, 2007; Freire-González, 2010). The intuition behind this effect is that an increase in the efficiency of using a given resource (e.g. energy) reduces the unitary cost of the service it provides (e.g. heating), from which follows an increase in its demand and the consequent offsetting of some or all of the initial expected savings.² This is generally known as the direct rebound effect (Greening et al., 2000). However, additional effects arise from an energy efficiency improvement, as there is also an increase of the available income that can lead to additional final demand for other products and services. This may in turn require such resource during their life cycle (from extraction to final disposal). This is commonly known as the indirect rebound effect (ibid.).³ Both effects have been extensively analysed for energy uses, but less for other natural resources (Font Vivanco and van der Voet, 2014). This is due to several reasons: the energy crisis in the 1970s and its importance in economic systems; the importance of energy in GHG emissions and global warming; energy dependence and geostrategic reasons, etc. A key question is thus how energy efficiency and its associated rebound effects affects the global use of natural resources other than energy. A better understanding of this question can help to anticipate unforeseen consequences, identify trade-offs and co-benefits and find optimal solutions between environmental problems.

² In this context, Becker's (1965) household production framework is useful to understand the demand of services provided by resources like energy.

³ Literature also identifies economy-wide effects: they imply changes in prices, supplies and demands through the overall economic system. Increases in the overall economic productivity are usually also included in this typology, although they have other implications.

Empirical evidence shows that the indirect rebound effect is a key driver of the overall rebound effect in many cases (Chitnis et al., 2013, 2014; Font Vivanco et al., 2014; Zhang et al., 2017), and consequently an important body of research has focused on its study (Druckman et al., 2011; Sorrell, 2007). Research on the indirect rebound effect shows that energy efficiency improvements generally lead to monetary savings that can be re-spent on other goods and services, in turn increasing the overall energy consumption (Druckman et al., 2011; Freire-González, 2011; Thomas and Azevedo, 2013a, 2013b; Chitnis et al., 2014; Freire-González et al., 2017). In some cases, the indirect effect can even play a major role in superseding any energy savings (Druckman et al., 2011; Font Vivanco et al., 2015; Zhang et al., 2017), a case commonly known as ‘backfire effect’ (Saunders, 2000). Some authors argue that, because goods and services are associated with multiple environmental pressures during their life cycle, such as waste and various air emissions, the indirect rebound effect can be expressed through various metrics (Alfredsson, 2004; Font Vivanco et al., 2014; Takase et al., 2005; Thiesen et al., 2008). Such a broader interpretation has sometimes been framed within the ‘environmental rebound effect’ (ERE) concept, which generalises the traditional energy rebound effect to encompass efficiency changes and indicators of interest that go beyond energy and energy-related emissions to a wide range of environmental issues (Font Vivanco et al., 2016; Goedkoop et al., 1999; Murray, 2013). Furthermore, the ERE approach has also incorporated other key characteristics from environmental-economic models, especially life cycle assessment and environmentally-extended input-output analysis. Specifically, the life cycle perspective, the high technology detail, and the use of environmental impact indicators (e.g. impact on ecosystems) (Weidma et al., 2008). Nevertheless, the study of rebound effects in the context of multiple environmental pressures, defined here as ‘cross rebound effects’, is in its infancy, with only a handful of empirical estimates available. Further research can provide a better understanding on the underlying reasons and the implications of such combined effects, including trade-offs, co-benefits and the possibility of backfire.

1.2. Objectives and structure of the paper

This research aims at developing a methodological framework that generalises the method to obtain the direct and indirect rebound effect of energy efficiency improvements in final demand uses, not only to energy consumption, but also to other natural resources. To this end, we develop the concept of the direct and indirect cross rebound effect, and apply it to estimate the impact of energy efficiency on the use of different natural resources in Spain. Specifically: energy, fossil fuels, metal ores, non-metallic minerals and water. This method allows to assess the increase/decrease in

the global use of other natural resources following an energy efficiency variation in final demand uses. The direct and indirect cross rebound effect is an indicator analogous to the direct and indirect rebound effect that provides information on the overall effect.

Section 2 describes the proposed methodology to assess the direct and indirect cross rebound effect at the household (or final demand) level. Section 3 describes the data for the case study. Section 4 provides estimates of the direct and indirect cross rebound effects and a discussion of the results, and section 5 shows the most relevant conclusions of the study.

2. Methods and models

The methodology described in this section is inspired by different academic backgrounds, but mostly from the direct and indirect rebound literature for energy efficiency. Some adaptations, however, are needed for its generalisation to other natural resources. Given that an improvement in energy efficiency has effects on the size and allocation of the final consumption, it has effects not only on indirect energy usage, but also on the indirect use of other resources. This consideration looks intuitive from a life cycle assessment perspective, where each unit of final consumption is associated with resource use over all its life cycle, including the extraction, production, use and waste management stages. So, how does the indirect rebound effect from an energy efficiency improvement affect the use of other natural resources beyond energy? To address this question, it is necessary a broad perspective and a thorough analysis of the indirect effects of energy efficiency improvements.

Particularly, Freire-González (2011) developed a framework for direct and indirect energy use from energy efficiency improvements in households (and other final demand uses) that can be adapted and generalized for other natural resources. Following this framework, three different steps are combined in this research, each using different methods. First, the use of econometrics and energy demand models to obtain the direct rebound effect from price-elasticity of demand for energy; second, the use of a re-spending model to allocate households' monetary savings from energy efficiency to other goods and services, considering households' budgets, and according to different scenarios; and third, an estimation of the direct plus indirect use of other natural resources from

the new consumption pattern through the use of an environmental extended input-output framework (Miller and Blair, 2009).⁴

2.1. Direct energy rebound effect

The direct rebound effect for energy uses is the most analysed issue in both the theoretical and empirical rebound literature. There are well-established standard methods to obtain the direct rebound effect from energy services, and empirical evidence is sound (Sorrell, 2007). The most common way to estimate the direct rebound effect is through the use of elasticities of demand. The direct rebound effect can be defined as (Khazzoom, 1980; Berkhout et al., 2000; Dimitropoulos and Sorrell, 2006; Sorrell, 2007):

$$\vartheta_{\varepsilon}(x_E) = \vartheta_{\varepsilon}(S_E) - 1 \quad (1)$$

where $\vartheta_{\varepsilon}(x_E)$ is the efficiency elasticity of the demand for energy and $\vartheta_{\varepsilon}(S_E)$ is energy efficiency elasticity of the demand for useful work for an energy service. When the energy efficiency elasticity of the demand for useful work for an energy service is equal to zero, there is no direct rebound effect. When $\vartheta_{\varepsilon}(S_E) > 0$, so $|\vartheta_{\varepsilon}(x_E)| < 1$ there is a positive direct rebound effect. Finally, when $\vartheta_{\varepsilon}(S_E) > 1$, so the demand is elastic, would produce "backfire" (Saunders, 1992).

However, under certain assumptions, the rebound effect can also be obtained from the own price-elasticity of the demand for energy. Under this approach, the following equation can be obtained (Khazzoom, 1980; Binswanger, 2001; Berkhout et al., 2000; Dimitropoulos and Sorrell, 2006; Sorrell, 2007):

$$\vartheta_{\varepsilon}(x_E) = -\vartheta_{PE}(x_E) - 1 \quad (2)$$

where $\vartheta_{PE}(x_E)$ is the own price elasticity of the demand for energy. This expression is based on two main assumptions. The first one is that responses to decreasing energy prices are the same than responses to energy efficiency –this is known as the ‘symmetry assumption’–. The second one, known as ‘exogeneity assumption’, states that energy efficiency is not affected by changes in energy prices.

⁴ Recent studies related to the use of input-output analysis to account for embodied energy and other natural resources are: Alcántara et al. (2017), Zhang et al. (2017), Xia et al. (2017) and Wijayasundara (2017).

2.2. The re-spending model

The re-spending model is the link between the energy efficiency improvement and the resource input-output model. We will model it following Freire-González (2011), Druckman et al. (2011) and Thomas and Azevedo (2013a, 2013b). The increase of resources use due to the re-spending effect can be defined as:

$$\Delta Re = \sum_{i=1}^n u_i \Delta x_i p_i + u_s \Delta s \quad (3)$$

where u_i is an operator that turns variations of final demand from monetary savings into variations of resource use, $x_i p_i$ is the demand of sector i (composed of quantity $[x]$ and price $[p]$), u_s is an operator that turns variations of savings into variations of resource use, and s are savings. For household expenditures u_i is represented in this modelling framework through $R(I - A)^{-1}$ from the input-output model of equation [10].

The households' budget equilibrium can be defined as follows:

$$y = x_E p_E + \sum_{i=1}^n x'_i p_i + s \quad (4)$$

or:

$$\Delta y = \Delta x_E p_E + \sum_{i=1}^n \Delta x'_i p_i + \Delta s \quad (5)$$

where y is the household income or the total budget, x_E is the amount of energy, p_E is the price of energy, x'_i are other goods and services different from energy supply, p_i is the price of the good or service i , and s are the monetary savings.

The marginal propensity to save can be defined as $\alpha = \frac{\Delta s}{\Delta y}$. From this equation: $\Delta s = \alpha \Delta y$. If this equation is inserted into equation [5] and some arrangements are made:

$$(1 - \alpha) \Delta y = \Delta x_E p_E + \sum_{i=1}^n \Delta x'_i p_i \quad (6)$$

Equation [6] shows the increase of final demand (endogenous variable) as a result as an increase in expenditures on the energy sector ($\Delta x_E p_E$) and on the other goods and services ($\sum_{i=1}^n \Delta x'_i p_i$) (exogenous variables in this case, although affected by energy efficiency). The sequence is: there is an increase of energy efficiency, then, due to the direct rebound effect there is an increase of expenditures on the energy sector and monetary savings; finally, these savings lead to an increase of expenditures in other goods and services.

The direct rebound effect defines the increase in expenditures on the energy sector ($\Delta x_E p_E$) and other monetary savings (if direct rebound is lower than 100%). The income elasticity of expenses defines how these savings are reallocated among different goods and services.⁵ The income elasticity of expenses can also be defined as:

$$\vartheta_y(x_i) = \frac{\Delta x_i p_i}{\Delta y} \frac{y}{x_i p_i} \quad (7)$$

2.3. Resource input-output model

In order to obtain the total resource use under several re-spending scenarios, a generalized input-output model can be built. This is a specific case of an environmental extended input-output model for different natural resources used in the production process (Miller and Blair, 2009). This model allows to obtain the total resource use –both direct resource use and their corresponding upstream requirements– from different final demand or final consumption patterns. We can start from the expression:

$$Re = Rx \quad (8)$$

where Re is a matrix of total use of different natural resources by different economic sectors, R is a matrix of resource intensities or direct use coefficients for different natural resources by different economic sectors. and x is a vector of sectoral output. On the other side, the traditional Leontief model can be expressed as (Leontief 1941):

$$x = (I - A)^{-1} f \quad (9)$$

⁵ Although different re-spending scenarios are also allowed. For more detail on the re-spending model and additional interpretation see Freire-González (2011).

where $(I - A)^{-1}$ is the inverse matrix of the Leontief production model, and f is the final demand vector for economic sectors. If equation [4] is inserted in equation [3], the next expression can be obtained:

$$Re = R(I - A)^{-1}f \quad (10)$$

This equation provides the total use for a set of natural resources from a given final demand. This formulation can also be expressed in terms of changes in final demand, which would yield the corresponding changes in total resource use.

2.4. Direct and indirect cross rebound effect

A new concept can be defined that relates the change in energy efficiency with the change in resource use. The direct and indirect cross rebound effect (*DICRE*) is an increase in other resource use after an energy efficiency improvement, due to the increase of available income. This effect can be mathematically defined as follows:

$$DICRE = \frac{\text{Calculated resource savings} - \text{Real resource savings}}{\text{Calculated resource savings}} \quad (11)$$

The calculated resource savings –without rebound– can be named as H , and the additional resource use given by the rebound and re-spending effect Re . This concept is somewhat different than the rebound effect as traditionally defined, although it has the same logic. The main difference consists on the understanding of the ‘calculated resource savings’ for other natural resources. One can assume that, after an energy efficiency improvement, there are no expected savings of other resource use. However, from a global perspective, and considering indirect effects, we can assume that some reduction is expected as less income is allocated to the energy sector, thus generating less global resource use. These effects can be understood and accounted using input-output and/or life-cycle assessment methods (Font Vivanco et al., 2016). We refer to section 2.3 for a detailed description of the input-output model proposed in this research.

From this perspective, the direct and indirect rebound effect can be formulated as:

$$DICRE = \frac{\Delta H - (\Delta H - \Delta Re)}{\Delta H} = \frac{\Delta Re}{\Delta H} \quad (12)$$

From equation (7) we know that:

$$\Delta x'_i p_i = \vartheta_y(x'_i) \frac{\Delta y}{y} x'_i p_i \quad (13)$$

If we now insert [13] into [6]:

$$(1 - \alpha)\Delta y = \Delta x_E p_E + \sum_{i=1}^n \vartheta_y(x'_i) \frac{\Delta y}{y} x'_i p_i \quad (14)$$

From this equation we obtain:

$$y = \frac{\sum_{i=1}^n \vartheta_y(x'_i) x'_i p_i \Delta y}{(1 - \alpha)\Delta y - \Delta x_E p_E} \quad (15)$$

Substituting equation [15] into equation [13] and arranging:

$$\Delta x'_i p_i = \vartheta_y(x'_i) \left[\frac{(1 - \alpha)\Delta y - \Delta x_E p_E}{\sum_{i=1}^n \vartheta_y(x'_i) x'_i p_i} \right] x'_i p_i \quad (16)$$

Now, from equation [3], and assuming that $\Delta s = \alpha \Delta y$:

$$\Delta Re = \sum_{i=1}^n u_i (\Delta x'_i p_i + \Delta x_E p_E) + u_s \alpha \Delta y \quad (17)$$

Using equation [16] inside [17] and rearranging terms:

$$\Delta Re = \sum_{i=1}^n u_i \left(\vartheta_y(x'_i) \left[\frac{(1 - \alpha)\Delta y - \Delta x_E p_E}{\sum_{i=1}^n \vartheta_y(x'_i) x'_i p_i} \right] x'_i p_i + \Delta x_E p_E \right) + u_s \alpha \Delta y \quad (18)$$

Then, from this equation and [12], a new formula for rebound effect can be obtained:

$$DICRE = \frac{\Delta Re}{\Delta H} = \frac{1}{\Delta H} \left(\sum_{i=1}^n u_i \left(\vartheta_y(x'_i) \left[\frac{(1 - \alpha)\Delta y - \Delta x_E p_E}{\sum_{i=1}^n \vartheta_y(x'_i) x'_i p_i} \right] x'_i p_i + \Delta x_E p_E \right) + u_s \alpha \Delta y \right) \quad (19)$$

This formula provides the direct and indirect cross rebound effect for energy efficiency improvements in households. It is estimated from energy savings estimated without considering the rebound effect (ΔH); monetary savings (Δy) from improving energy efficiency of a particular energy service in households, the marginal propensity to save (α); expenditures on goods and services ($x'_i p_i$) and expenditure on energy ($x_E p_E$), which conform the pattern of household consumption. Variable ($x'_i p_i$) is exogenously set from the re-spending scenarios. Finally, the income elasticity of the expenditure of several goods and services ($\vartheta_y(x'_i)$) determines the variation in the spending on such goods and services.

In order to account for the changes in consumption patterns induced by an energy efficiency improvement in final demand (households) we will follow Freire-González (2011) steps. Starting from the budget equilibrium:

$$y = x_E p_E + \sum_{i=1}^n x'_i p_i + s \quad (20)$$

Assuming that income and energy prices remain constant:

$$\sum_{i=1}^n x'_i p_i = y - x_E p_E - s \quad (21)$$

This expression can also be expressed as:

$$\sum_{i=1}^n x'_i p_i = y - (x_E + \Delta x_E) p_E - s \quad (22)$$

$$\sum_{i=1}^n x'_i p_i = y - \left(1 + \frac{\Delta x_E}{x_E}\right) p_E - s \quad (23)$$

The literature suggests that under the assumptions of exogeneity and symmetry, direct rebound effect can be estimated from the price elasticity of the demand of energy (see equation [2]): $\vartheta_\varepsilon(x_E) = -\vartheta_{PE}(x_E) - 1$. The general definition of the rebound effect is:

$$\vartheta_\varepsilon(x_E) = \frac{\Delta x_E}{\Delta \varepsilon} \frac{\varepsilon}{x_E} \quad (24)$$

With equations [24] and [23] we can obtain:

$$\sum_{i=1}^n x'_i p_i = y - \left[1 + (-\vartheta_{PE}(x_E) - 1) \frac{\Delta \varepsilon}{\varepsilon}\right] x_E p_E - s \quad (25)$$

where $\frac{\Delta \varepsilon}{\varepsilon}$ is the increase in energy efficiency. In this context, energy efficiency is defined as the percentage reduction of energy expenditure by households, as implicitly defined in equation [25]. So, if efficiency improves, the cost of the relevant energy service is reduced, and so is the initial expenditure on the energy sector. It is assumed that this expenditure reduction is in the percentage specified in $\frac{\Delta \varepsilon}{\varepsilon}$. This is consistent with standard definitions of the direct rebound effect coming from own price demand elasticities (as the one used in this research). However, more complex definitions of energy efficiency can be introduced in this framework in further research. This equation estimates the direct and indirect cross rebound effect of energy efficiency improvements under different re-spending scenarios, using the own price elasticity of the demand for energy. For illustrative purposes, the assumption that there are no monetary savings has been imposed for equation [25].

As shown in Freire-González (2011), different potential re-spending scenarios are possible using equation [25]. In order to simplify the analysis, a proportional re-spending scenario has been assessed in this study. In this scenario, monetary savings are reallocated according to the share of each good or service on the total households' budget, i.e., the new income generated by an energy efficiency improvement is spent in the same way that before. Input-output data contains information on households' final demand. The proportional re-spending scenario is exogenously formulated as:⁶

$$x_i^p p_i = x_i p_i \left[1 + \frac{x_E p_E \left(1 - \left[1 + (-\vartheta_{PE}(x_E) - 1) \frac{\Delta \varepsilon}{\varepsilon} \right] \right)}{\sum_{i=1}^n x_i p_i} \right] \quad (26)$$

Equation [26] defines the new households' expenditure on different goods and services using an estimation of the direct rebound effect (own price energy elasticity) and considering a proportional scenario for new income allocation. There are also other possibilities in reallocating new income like the use of income elasticities or other more sophisticated econometric approaches (like the estimation of Almost Ideal Demand Systems). These approaches, however, require comprehensive data on all goods and services detailed in the input-output system, which are not currently available. Further research can improve this aspect.

⁶ For more details on the derivation of these scenarios see Freire-González (2011).

3. Data

3.1. Direct rebound effect

The first step is to provide estimates of the direct rebound effect via own price elasticities of the demand for energy for residential uses. In order to account for this effect, and before reallocating the new available income, it is necessary to obtain estimations for it. A straightforward way shown in the literature to obtain the direct rebound effect is by using own price elasticities of the demand for the relevant energy service. As shown in previous sections, literature states that, under some circumstances, they can be used to obtain a proxy of the direct rebound effect, by assuming that an efficiency improvement equals to a reduction in marginal cost of the relevant service. However, despite this is a useful and easy way to estimate them, we have to be aware that this approach tends to overestimate rebound effects (Sorrell, 2007).

A commonly used approach to estimate price elasticities is to specify a demand model for residential energy uses. The estimation of the model can be conducted using a logarithmic functional form provides elasticities of the estimated parameters:

$$\ln E = \beta_0 + \beta_1 \ln P_E + \beta_2 \ln P_{it} + \beta_3 \ln Y + \beta_4 \ln C + \beta_5 \ln Z + u \quad (27)$$

Equation [27] shows a general econometric model where energy demand E depends on the price of energy P_E , the prices of other goods and services P_{it} , the disposable income Y , weather conditions C and other factors Z . In this specification, the value of β_1 provides the own price elasticity of demand for energy, and then, a proxy of the direct rebound effect for that specific energy source or service. Estimations of the own price elasticities of the demand for residential energy uses can be found in literature for different countries/regions. There are a several surveys and other research studies that estimate elasticities using different methods and data, and some interesting and comprehensive literature reviews (e.g.: Atkinson et al., 1995; Brons et al., 2008; Suganthi et al., 2012; etc.).

For illustrative purposes we have conducted a sensitivity analysis using a range between 0 and -1 for residential demand. We can then assume that the direct rebound effect for domestic uses would range between 0%-100%. That means that an efficiency improvement expected to reduce 100 units

of energy consumption in households would finally reduce it between 100 - 0. In any case, whatever the elasticity value is finally chosen for analytical purposes, the final use of energy as a result of direct rebound effect is not expected to increase from the direct rebound effect perspective, since most studies show that energy demand for most uses in industrialized countries is inelastic, so minor than 1.

3.2. Environmentally extended input-output tables

The empirical analysis has been carried out using Exiobase v.2, an environmentally-extended multi-regional input-output database (Tukker et al., 2013; Wood et al., 2015). For the year 2007, Exiobase v2 contains annual monetary transactions between 163 industries and final users across 48 regions (43 of the largest world economies and 5 continent regions aggregating the rest of the world). Exiobase v2 also contains several environmental accounts in physical units that provide data on energy use, biotic and abiotic resources, and air emissions, among other, at the same industry and country detail. The Spanish input-output table and its different satellite accounts for the different resources has been isolated.⁷ These additional accounts on different resources use are for: energy (total energy carrier use), fossil fuels, metal ores, non-metallic minerals and water (green and blue water consumption).

4. Results and discussion

This section contains the development of an application of the described method for estimating the effects of energy efficiency improvements in households in Spain for the selected natural resources. Specifically, we have computed the total use of fossil fuels, water, metal ores, non-metallic minerals and energy use, after an energy efficiency improvement in households in the Spanish economy and the DICRE for all these resources in Spain.

Five generalized input-output models have been built following the methodology shown in section 2.3, one per each selected natural resource.⁸ Then the cross rebound effect has been estimated in

⁷ By using an input-output table of one region we are assuming that imports are produced by using the same technology as domestic production. This is known as domestic technology assumption in the I-O literature. This would produce a bias in results, that some studies suggest could be important (see Rocco and Colombo, 2016). This is however an illustrative exercise on how to apply the proposed method, that would be easily adapted to a multiregional framework.

⁸ As mentioned in section 3.2, Exiobase provides data on the use of the different natural resources. For more detailed information on the data and definitions see Tukker et al. (2013) and Wood et al. (2015).

each of them under different assumptions on energy efficiency improvements in households and using different own price elasticities of energy. The results in terms of total variation of different natural resources use from the simulations can be seen in figures 1-5.

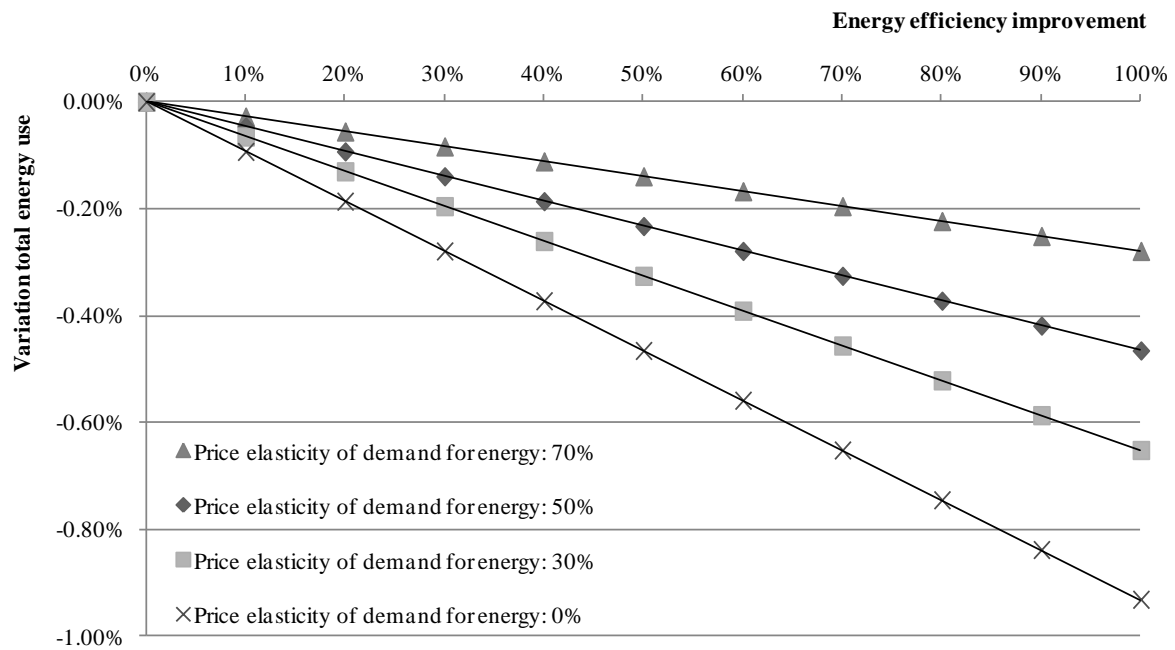


Figure 1 Energy variation after an energy efficiency improvement in households in Spain under different scenarios.

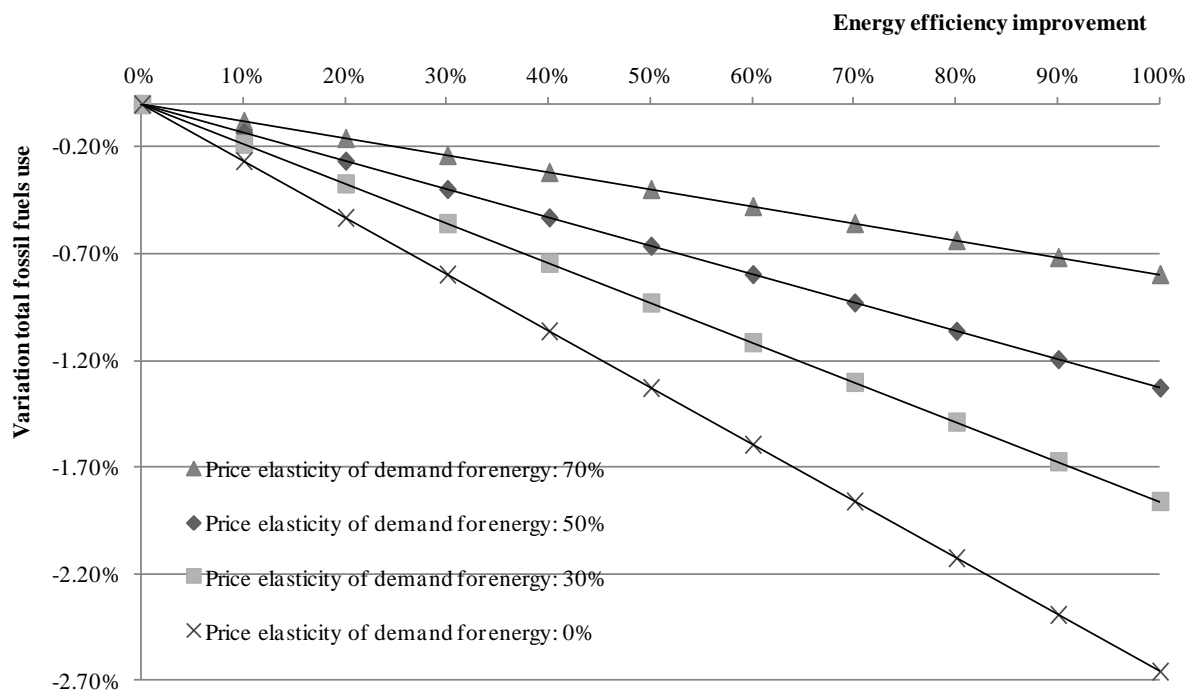


Figure 2 Fossil fuels variation after an energy efficiency improvement in households in Spain under different scenarios.

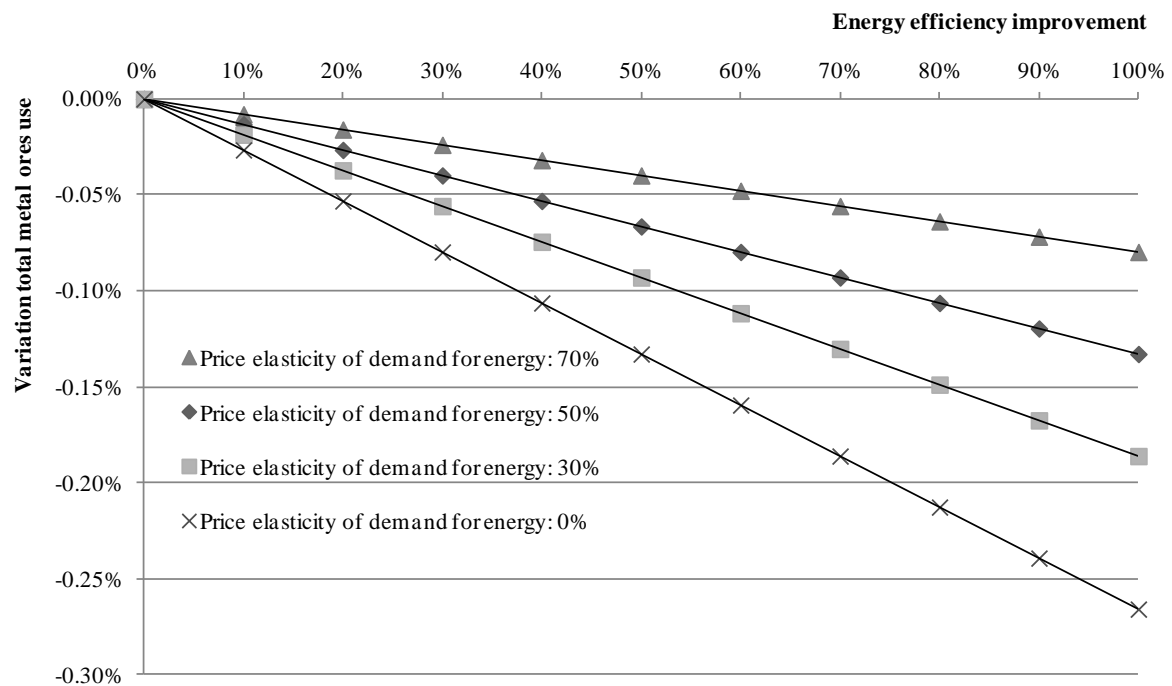


Figure 3 Metal ores variation after an energy efficiency improvement in households in Spain under different scenarios.

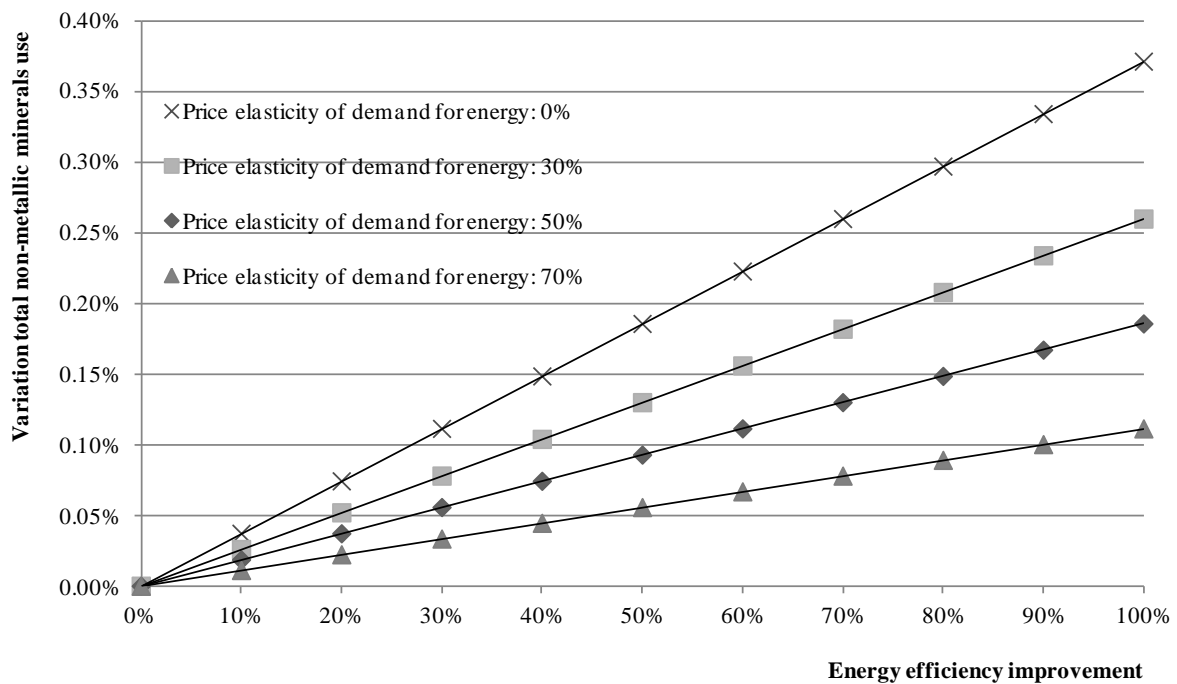


Figure 4 Non-metallic minerals variation after an energy efficiency improvement in households in Spain under different scenarios.

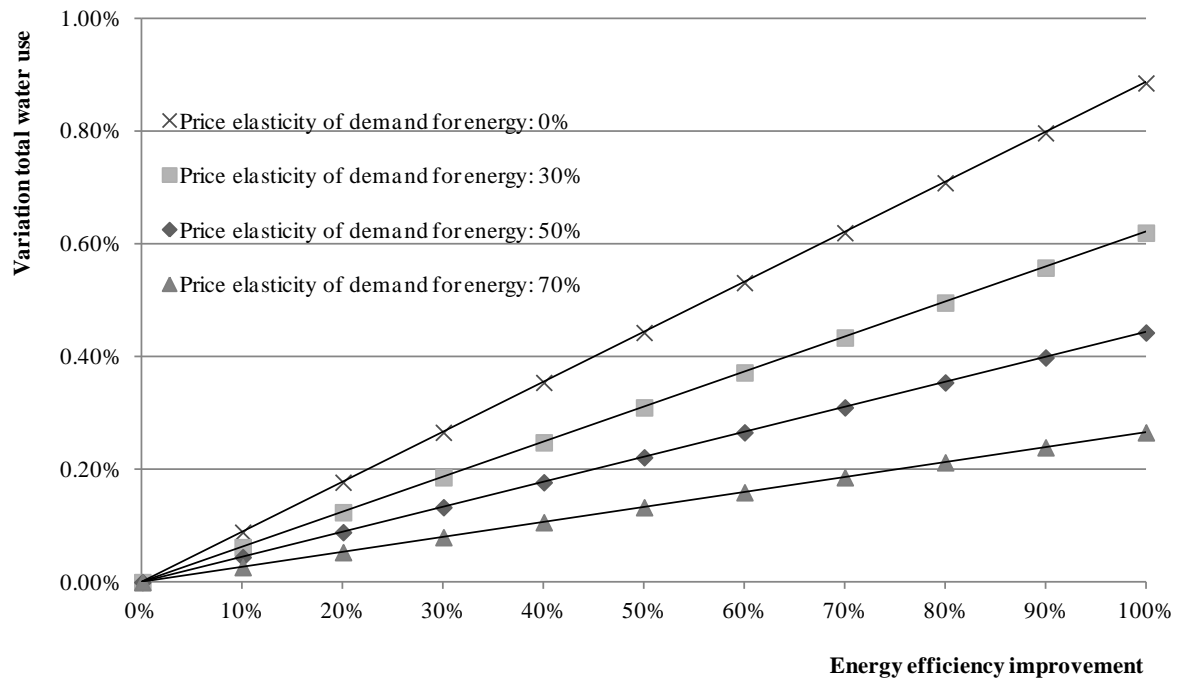


Figure 5 Water variation after an energy efficiency improvement in households in Spain under different scenarios.

Figures 1-5 show how, after different levels of energy efficiency improvements in households, there is a reduction of the total (direct and indirect) use of different resources: energy, fossil fuels and metal ores; and an increase of the consumption of non-metallic minerals and water. The size and direction of the variation depends in each case on the economic structure, the energy efficiency improvement, and the own price elasticity of the demand of energy. However, the economic structure and the resource consumption structure are the most determinant factors. Other economic structures with different resource intensities and economic relationships would lead to different results. The linearity of the results (see all figures) is due to the proportional coefficients assumptions inherent in input-output models, and the linearity of the different energy efficiency scenarios.

Table 1 shows the DICRE of the specific case of Spain for the different natural resources analysed, following the methodology described in section 2.

Table 1 Direct and indirect cross rebound effect for selected natural resources from energy efficiency improvements in Spanish households.

| Resource | Price elasticity of the demand for energy |
|----------|---|
|----------|---|

| | 0 | -0.3 | -0.5 | -0.7 | -1 |
|---|---------------|---------------|---------------|---------------|-------------|
| <i>Energy (Direct and indirect rebound effect)</i> | 49.42% | 64.60% | 74.71% | 84.83% | 100% |
| Fossil fuels | 25.18% | 47.63% | 62.59% | 77.56% | 100% |
| Metal ores | 77.53% | 84.27% | 88.77% | 93.26% | 100% |
| Non-metallic minerals | 167.26% | 147.08% | 133.63% | 120.18% | 100% |
| Water | 2,283.34% | 1,628.34% | 1,191.67% | 755.00% | 100% |

There are strikingly different values of DICRE between energy efficiency and other natural resources analysed, depending on the economic structure composition, the natural resource analysed, and the price elasticity of the demand for energy. The results of the DICRE in terms of energy, which is what the research on the rebound effect typically assesses, and assuming a price elasticity between -0.3 and -0.5 (as the literature suggests for Spain [Freire-González, 2017]), are between 64.6%-74.7%.

The DICRE for fossil fuels is lower than the one for energy, concretely between 48%-63% (assuming the same elasticity range). This means that an energy efficiency improvement would only reduce approximately half of the expected reduction of fossil fuels. A similar case can be found regarding metal ores, but with even less final savings due to a high DICRE of between 84%-89%. The DICRE results for non-metallic minerals and water use describe an increase of their overall use after an energy efficiency improvement in households. The results for water show a particularly high rebound effect, higher than 2,000% in the most extreme case, meaning that energy efficiency improvements in households trigger a notable net increase in the use of these resources. In these cases, we observe a special case of the Jevons Paradox (Jevons, 1865), but applied to other natural resources. In other words, following energy efficiency improvements and its associated DICRE, we observe co-benefits in the form of net reductions in fossil fuels and metal ores, and trade-offs via net increases in non-metallic minerals and water use. The remarkably high cross rebound effect in water use, although shocking, is not surprising as the cross rebound effect is different than the traditional definition of the (energy) rebound effect. The released monetary resources from an energy efficiency improvement triggers a new consumption pattern that have a lot more embodied water than the previous consumption pattern.

Our results are to some extent consistent with some of the related literature. Concretely, Thiesen et al. (2008), Font Vivanco et al. (2014) (2015), and Takase et al. (2005) found a wide range of rebound effect estimates when using various environmental indicators. In this sense, Font Vivanco

(2016) argues that the consideration of the life cycle burdens in terms of multiple environmental indicators can cause such wide variations in the rebound magnitude, including an increased occurrence of backfire effects. A key reason is the asymmetry in the resource use intensity associated with the final demand categories: some resources such as energy are evenly used across economic sectors, while others such as water concentrate on a few sectors (e.g. agriculture) (Peters et al., 2016). Consequently, the reallocation of expenditure from resource non-intensive to resource intensive final demand categories can cause such variations via the indirect rebound effect. This is the case of the cross rebound effect in terms of water use in our case study, as its remarkable magnitude is largely caused by additional expenditures on water-intensive products and services such as foodstuffs and catering services. Moreover, Thomas and Azevedo (2013a, 2013b) analysed direct and indirect rebound effects from residential energy efficiency investments in terms of energy, CO₂, NO_x, and SO₂, and found moderate differences between these indicators. Our results may thus suggest that the consideration of broader environmental indicators, especially those not directly related to energy use, can introduce higher variability in the rebound magnitude from energy efficiency improvements.

5. Conclusions

As the rebound effect literature has demonstrated, energy efficiency improvements can be less effective than expected in reducing energy consumption due to the economic agents' behaviour. If we assume that an energy efficiency improvement increases the available income due to the reduction of energy costs, we find not only an increase of indirect use of energy, but also an additional variation of other natural resources' use. This research demonstrates that, expanding the indirect rebound framework to other resources and using input-output techniques, an energy efficiency improvement triggers relevant changes in the indirect consumption of other natural resources.

Our findings suggest that conceiving rebound effects beyond energy indicators is key to assess the complete consequences of energy efficiency policies. Such consequences can be understood in terms of three effects: co-benefits, trade-offs and backfire. In this context, co-benefits and trade-offs take place when a reduction in energy use leads to an overall reduction or increase in another resource, respectively. A better understanding of these effects can be valuable to inform integrated environmental policies (e.g. joint energy and water efficiency policies) and increase the effectiveness of achieving environmental targets. These features resonate with the resource nexus and related

frameworks (Andrews-Speed et al., 2014), and suggests synergistic research avenues, including finding optimal solutions between competing interests (Bizikova et al., 2013). Lastly, fears of backfire effects have been looming the academic and policy arenas since the early works of Stanley Jevons, yet limited evidence has supported their occurrence so far (Jenkins et al., 2011). Our findings, in line with other applications of the environmental rebound effect concept (Font Vivanco et al., 2016), suggest that the consideration of non-energy natural resources has important implications for the likelihood of such backfire effects. This has deep policy implications in the context of achieving critical sustainability goals, as rebound effects are sometimes downplayed (Gillingham et al., 2013).

Regarding the Spanish case, we observe that energy efficiency increases the use of some of the analysed natural resources and reduces the use of some others. The results show that an energy efficiency improvement in households could increase the use of minerals and water, while reducing the use of energy, fossil fuels and metal ores. These reductions, however, are lower than the expected ones from an input-output perspective, leading to positive direct and indirect cross rebound effects: between 64.6%-74.7% for energy (equivalent to the combined direct and indirect rebound effect); 48%-63% for fossil fuels; 84%-89% for metal ores; backfire for non-metallic minerals (147%-134%) and extreme backfire for water (1,191%-1,628%). While not general patterns are observed, it is quite straightforward to track how different resources or materials are affected by using input-output or life cycle assessment techniques. Additional data on the use of natural resources linked to national accounts is needed to conduct more comprehensive empirical analyses of energy efficiency effects on resources use.

Beyond the contribution of this article to the rebound effect theoretical and empirical literature, this research also contributes to the Input-output modelling literature, and specifically to the environmentally extended input-output literature, by setting a method to assess the impacts of energy efficiency on the use of natural resources. Besides, although this method has been developed for energy efficiency, it opens the door to further developments and its generalisation for productivity improvements of other natural resources.

New metrics on efficiency improvements and global natural resources are needed to compute the total effect of productivity improvements and resources use. Further theoretical and empirical research is needed to improve this framework, and more data is needed in order to provide more empirical analyses for different countries and different natural resources, especially those that are

critical for economies and for ecosystems as well as non-renewable. Policy-makers should take into account the results of this study for the design and implementation of energy policies.

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Annex. List of symbols and acronyms

| | |
|--------------------------------|--|
| ERE | Environmental rebound effect |
| $DICRE$ | Direct and indirect cross rebound effect |
| GHG | Greenhouse gas emissions |
| $\vartheta_{\varepsilon}(x_E)$ | Efficiency elasticity of the demand for energy |
| $\vartheta_{\varepsilon}(S_E)$ | Energy efficiency elasticity of the demand for useful work for an energy service |
| $\vartheta_{PE}(x_E)$ | Own price elasticity of the demand for energy |
| $\vartheta_y(x_i)$ | Income elasticity of the expenditure of the good or service i |
| Re | Total resources use |
| H | Engineering calculated resource savings |
| R | Matrix of resource intensities or direct use coefficients |
| x | Vector of sectoral output |
| $(I - A)^{-1}$ | Inverse matrix of the Leontief production model |
| u_i | Operator that turns final demand into variations of resource use |
| u_s | Operator that turns savings into variations of resource use |
| $x_i p_i$ | Demand of good or service i |
| $x_i^P p_i$ | Demand of good or service i under the proportional scenario |
| $x_E p_E$ | Demand of energy sector E |
| $x'_i p_i$ | Demand of non-energy goods and services |
| y | Disposable income |
| s | Savings |
| f | Final demand of goods and services |
| α | Marginal propensity to save |
| ε | Energy efficiency coefficient |
| E | Energy demand |
| P_E | Price of energy |
| P_i | Price of non-energy goods and services |
| C | Weather conditions |
| Z | Other factors affecting energy demand |
| u | Error term in econometric estimates |
| β | Estimated coefficients in econometric estimates |