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Decomposition and measurement of the rebound effect: The case of energy efficiency improvements in Spain

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HIGHLIGHTS

- The study fills a gap in literature by breaking down the energy rebound effect.
- The Spanish economy is taken as a case study.
- The Direct Rebound Effect explains around 10% of the total effect.
- Indirect Rebound Effect values range between 1.2% and 1.8%.
- Economy-wide Rebound Effect values range from −4.51% to 128.45%, with no clear trend.

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ABSTRACT

The rebound effect caused by energy efficiency improvements demands greater attention from energy policy-makers as it represents an important obstacle to energy consumption reduction measures. Despite the emerging literature about the rebound effect, no studies to date have managed to break down it. To do so, this study introduces the disruptive innovation of replacing the Logarithmic Mean Divisia Index method used in previous literature with Structural Decomposition Analysis. Based on Input-Output tables, a re-spending model allows us to assess the Indirect Rebound Effect for 14 productive sectors. Finally, Structural Decomposition Analysis enables us to determine the Economy-Wide Rebound Effect caused by energy efficiency improvements. As far as we are aware, no other study to date has done so. Spain is used as a case study for the 2000–2014 period. Major findings indicate that total rebound effect varies from nearly to 10% to around 50%. The part of rebound explained by Direct rebound effect is around 10%. Indirect rebound effect shows values between 1.2% and 1.8%. Finally, Economic wide rebound effect varies from −4.51% to around 40% but without showing a clear trend for the period considered. The novelty of this study is that it attempts to break the overall rebound effect down to the direct, indirect, and economic wide rebound effect by combining the Cobb-Douglas production function and decomposition techniques.

1. Introduction

Energy efficiency has become a primary energy policy goal in many countries; this is certainly true for Spain, where major efforts in this regard have shaped the policies towards energy-intensive sectors [1,2]. When considering a ‘stated policies’ scenario[1], global carbon neutrality targets depend on 37% from energy efficiency improvements by 2050 [3]. In almost two decades, both the European Union (EU) and Spain achieved energy efficiency improvements such as a decrease in units of oil equivalent required per euro of GDP.

Energy efficiency improvements could lead to changes in the demand for energy services if the rebound effect offsets some of the energy savings achieved. Should this change take place, the potential abatement of greenhouse gas (GHG) emissions and energy savings due to energy efficiency improvements may not fully materialize [4,5]. Forecasts of energy savings could be overstated due to rebound effect. The

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[1] Following International Energy Agency criteria, the Stated Policies Scenario reflects the impact of existing policy frameworks and today’s announced policy intentions.

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rebound effect is defined as the additional energy consumption from overall changes in demand due to behavioral and other systemic responses to the energy efficiency improvements [6–9].

The rebound effect measures the fraction of energy efficiency improvements offset by an increase in energy consumption [10]. It corresponds to an unexpected increase in energy consumption due to the reduction of the effective cost providing a specific energy service. Energy efficiency seeks to reduce this cost [11].

Greening et al. [12], Sorrell [13] and Sorrell and Dimitropoulos [14] identified three types of rebound effect which lead to greater energy consumption, through three channels:

The *direct rebound effect* has an impact on the energy consumption of the energy service affected by the energy efficiency improvements. The cost of energy services decreases as energy efficiency improves. The downward price triggers a greater energy demand, which means more energy consumption. The impact of the effective energy cost reduction on consumption includes both the substitution effect and the income effect. The direct rebound effect stems from the responses of first-order consumers and producers to energy efficiency improvements. Consequently, the direct rebound effect ignores any changes in the demand for other goods and services due to either the change in relative prices or higher disposable income. For this reason, the direct rebound effect is defined by energy price elasticity (cost).

The *indirect rebound effect* affects the demand for goods stemming from changes in disposable income. Declining effective energy costs generate greater energy demand from downstream industries along the industrial chain. This second-order change is referred to as the indirect rebound effect and results in an increase in the overall energy demand [15]. Delving further into the matter, these authors note how most of the available literature estimates the indirect rebound effect by answering the question: if consumers (or productive sectors) are given an extra dollar, how will they spend it? This implies that the evaluation of the size of the direct rebound effect focuses on the price effect while the size of the indirect rebound effect is assessed through the income effect, using a spending model as if it were an input–output model.

Economy-wide effects go further than changes in energy service prices and disposable income. They stem from global economic readjustments following energy efficiency improvements, thus becoming the third-order response. The logic behind this concept is that an effective decrease in energy costs results in a reduction in the price of intermediate and final products, which leads to price adjustments throughout the whole economic system. The production-cost gap between energy-intensive industry and other industries thus narrows. A decrease in the relative price of energy-intensive products further increases consumption, thus leading to more energy consumption. Therefore, energy efficiency improvements can increase the energy demand of the entire economic system [16–18].

Previous studies have reviewed approaches to measuring the rebound effect but do not decompose it into its components. Currently, the literature has yet to find a way to break down the rebound effect into the direct rebound effect, indirect rebound effect and economic wide rebound effect. Various rebound effect policymakers and environmental agencies have echoed concerns raised by academics regarding the need to address the rebound effect to achieve full energy consumption, economic and environmental decoupling. However, due to a lack of consensus on how to measure it, these concerns have generally not been translated into a tangible policy action [19], thus acting as a barrier to evaluating the welfare implications of energy efficiency policies. As a consequence, despite the efforts made this key point remains unsolved. The overarching aim of this study is therefore to go further and bridge the gap in terms of how to break down and measure the rebound effect in order to contribute to the design of better energy efficiency actions. As far as we are aware, no study to date has attempted to do so.

The novelty of the work is twofold. First, we propose a new methodological approach to break down the rebound effect into the direct rebound effect, indirect rebound effect and economic wide rebound effect by combining the Cobb-Douglas production function and decomposition techniques. Our work also is the first to do it. Second, this paper applies the proposed method to Spain for the period 2000–2014. Spain is a representative case study of strong energy efficiency improvements-oriented policy measures. The period under study is determined by the availability of data. Recently, Lin et al. [16], Wang et al. [20] and Liu et al. [21] used the Logarithmic Mean Divisia Index (LMDI I) method and the Cobb-Douglas production function to assess direct rebound effect in Chinese industry.

Under the indirect rebound effect definition provided by Greening et al. [12], the effective decrease in utility energy costs could lower the price of energy-consuming products, leading to a rise in the demand for these products in the economic system, thus increasing the energy demand. This increase has an impact on macroeconomic activity through the inter-sectoral relationship described in Input-Output Tables (IOTs). For that reason, this research takes the methodological advance from Lin et al. [16], Wang et al. [20] and Liu et al. [21] as a starting point but contributes the disruptive innovation of replacing LMDI I with Structural Decomposition Analysis. The use of IOTs and a re-spending model allows this study to assess the indirect rebound effect as described below. Finally, Structural Decomposition Analysis enables us to capture the economy-wide rebound effect caused by the energy efficiency improvements. To calculate the economy-wide rebound effect, changes in inter-sectoral relationships must be accounted for, which lends support to the use of Structural Decomposition Analysis due to changes in IOTs from year to year. This is the main methodological contribution to the literature, but not the only one. The ultimate goal and the novelty of this study is that it attempts to break the overall rebound effect down to the direct, indirect, and economy-wide rebound effect by combining the Cobb-Douglas production function and decomposition techniques.

This paper is structured as follows: after the Introduction, a review of the literature is shown presented in Section 2. Section 3 details the methodology and materials used. The main results are detailed and discussed in Section 4, and the conclusions drawn are set out in Section 5.

2. Review of the literature

Considerable concerns have emerged in the field of energy economics due to the rebound effect primarily caused by the energy-saving effects of energy efficiency improvements. Most of the related articles focus on high emission areas or countries (i.e., EU countries, US and China) and the most energy-intense sectors (industry, transport or residential). A comprehensive summary of the findings in the literature on the rebound effect can be found in Sorrell [13] and Jenkins et al. [22]. An updated review is provided by Lin et al. [16], while the most recent review of the literature comes from Jin and Kim [23] and Safarzadeh et al. [18], with the latter reference referring to the industry sector only. A wide range of methodological approaches have been used to assess the rebound effect.

To capture the economy-wide rebound effect, the computable general equilibrium (CGE) model has been widely used. Turner [24] used a CGE framework to research the conditions under which the rebound effect may occur in response to increases in energy efficiency in the UK national economy. Hanley et al. [25] applied a similar approach for the Scottish economy. Turner and Hanley [26] used a CGE model for the same economy to analyze the factors influencing impacts of one form of technological change—improvements in energy efficiency—on absolute levels of CO_2 emissions, on the carbon intensity of the economy, and the per capita Environmental Kuznets Curve relationship. An article by Yu et al. [27] focusing on the state of Georgia, USA, is also worth citing. More recently, Bye et al. [28] applied a multi-sector CGE model to the Norwegian economy to explore the cost, emission, and energy rebound effects of alternative policy interpretations underlying the proposed 2030 energy efficiency goal.

As econometrics approach has also been widely used. Ouyang et al.

[29] first estimated an energy demand model to assess the magnitude of the rebound effect in Yangtze River Delta Urban Agglomeration industrial sectors by using dynamic Ordinary Least Squares regression and seemingly unrelated regression methods. Llorca and Jamasb [1] analyzed energy efficiency and the key features influencing the rebound effect for road freight transport in 15 European countries during the 1992–2012 period using a stochastic frontier analysis approach. Freire-González [30] developed a hybrid methodology combining econometric estimates, extended environmental input–output analysis, and re-spending models. The econometric total factor productivity (TFP) approach is usually the best way to represent the contribution of technological progress, with the Cobb-Douglas and CES production function being employed to estimate TFP. Yan et al. [17] used dynamic panel data models to estimate the economy-wide rebound effect for China's provinces.

Orea et al. [31] incorporated the measurement of the rebound effect into a stochastic energy demand frontier model and estimated the effect as indicated by Saunders [9]. These authors modified the conventional stochastic energy demand frontier model by adding an interaction term with the inefficiency term, which allowed them to estimate energy efficiency and the rebound effect simultaneously in a one-step procedure. Adetutu et al. [32] adopted a two-step strategy for measuring the energy rebound effect. In a first step, they used stochastic frontier analysis to measure the energy efficiency values. In a second step, they used a dynamic energy demand regression model in which a set of variables interacted with the term measuring energy efficiency.

Hediger et al. [33] linked econometrics with behavioral economics by researching how households respond to heating system efficiency improvements. In a similar vein, Santarius and Soland [34] addressed the current rebound discourse in psychological theories.

Along with the aforementioned approaches, decomposition techniques for measuring the rebound effect are also available in the specialized literature. For the most part, the decomposition analysis involves two methods: Index Decomposition Analysis (IDA) and Structural Decomposition Analysis. LMDI I is an IDA technique [35]; in fact, it is the most extensively applied model in the field of energy economics. Together with top-down models, decomposition models are among the most commonly used for the estimation of the rebound effect [18]. However, Structural Decomposition Analysis uses data from IOTs and offers a broader range of information for both technical aspects and the effects of the final demand than IDA does [36,37]. Typical Structural Decomposition Analysis studies can provide more detailed structural factors, such as the Leontief effect (or technical effect) [38] and also shape socio-economic drivers from both production and final demand perspectives. LMDI approaches differ from Structural Decomposition Analysis as they do not allow researchers to carry out an in-depth analysis of the internal production linkages within an economy, and their influence on the changes in GHG emissions or energy consumption levels [39]. IOTs help capture the indirect rebound effect and economy-wide rebound effect while LMDI does not. This is because IOTs involve macroeconomic inter-industry reactions to changes, meaning that the proposed methodology is capable of accounting for the indirect channels (indirect rebound effect and economy-wide rebound effect) through which the rebound effect operates. This represents one advantage when comparing with the literature on LMDI.

3. Method and materials

3.1. Method.

3.1.1. The energy rebound effect

The total rebound effect generated by technological progress in an economy can be defined as the ratio of the incremental energy consumption to the amount of energy savings caused by technological progress, as shown in Eq. (1).

$$RE_{t+1} = \frac{\text{Incremental energy consumption}}{\text{Amount of energy savings caused by technological progress}} = \frac{A_{t+1}(Y_{t+1} - Y_t)I_{t+1}}{Y_{t+1}(I_t - I_{t+1})} \quad (1)$$

where t denotes time; I_t is energy intensity in period t; Y_t denotes an output measure in period t (i.e., total gross added value); A_t denotes total productivity factor in period t; and, finally, RE_t represents the total energy rebound effect in period t expressed as the percentage of the forecast reduction in energy use lost due to the sum of the consumers', productive sectors' and market's responses to changes after energy efficiency improvements. It includes the direct rebound effect, indirect rebound effect and economy-wide rebound effect.

3.1.2. Direct rebound effect

To determine the direct rebound effect, the contribution of energy consumption to economic growth is assessed. It is assumed that energy efficiency improvements derive from technological progress, thus it is first necessary to calculate its contribution to economic growth—σ_t in Eq. (15) below. A neoclassical production function is considered in Eq. (2) as a starting point [40–42],

$$Y_t = A_t \cdot F(K_t, L_t, E_t) \quad (2)$$

where A_t represents technological progress in the sense of Solow [43] varying through time, K_t measures capital stock, L_t measures the labor force and E_t, energy consumption. The Cobb Douglas production function is used to estimate parameters as follows [44]:

$$Y_t = A_0 \cdot e^{rt} \cdot K_t^{\alpha} \cdot L_t^{\beta} \cdot E_t^{\gamma} \quad (3)$$

In Eq. (3) technological progress has a fixed value (A_0) and an unfixed one (e^{rt}) [45], α, β and γ parameters are the elasticities of economic growth to capital (K), labor (L) and energy consumption (E). Following Freire-González [11], under certain assumptions[2], elasticities of economic growth for energy consumption (E) may be considered as energy price elasticity, thus defining the direct rebound effect [1,46,15,47]. To soften out layers, natural logarithms are used:

$$\ln Y_t = \ln A_0 + rt + \alpha \ln K_t + \beta \ln L_t + \gamma \ln E_t \quad (4)$$

Parameters in Eq. (4) could be estimated with Ordinary Least Squares regression after checking the Engel-Granger test. However, when Variance Inflation Factor (VIF) values indicate multicollinearity problems, other types of regression techniques such as Ridge regression must be used [48].

Being A_t* the sum of lnA_0 and rt, natural logarithms are named Y_t*, K_t*, L_t*, E_t*, respectively. Eq. (4) may be written as:

$$Y_t^* = A_t^* + \alpha K_t^* + \beta L_t^* + \gamma E_t^* + u_t \quad (5)$$

[2] They are: (1) consumers' reaction to an efficiency improvement is similar to their reaction to a reduction in energy prices, (2) energy efficiency is not affected by energy prices.

where u_t is the stochastic term; for example, in Eq. (5) if γ is 0.1 it means that 10% of the increased income derived from the energy price reduction goes to a direct increase in energy consumption (direct rebound effect), and 90% goes to re-spending. This is thus the size of the second-order response or indirect rebound effect [15].

3.1.3. A re-spending model to assess the indirect rebound effect

Vivanco et al. [19] explained the use of a re-spending model and distinguished between the direct rebound effect and indirect rebound effect. In line with their concepts, one example of the rebound effect is the way in which fuel efficiency improvements in passenger cars have made driving cheaper; users then drive more and purchase larger fuel (direct rebound effect) and/or spend the remaining savings on other products (indirect rebound effect). The size of the final decisions could be assessed using a re-spending model [49].

The indirect rebound effect is assessed as values obtained from the direct rebound effect through a re-spending model based on IOTs. The direct rebound effect determines first-order energy savings after energy efficiency improvements, which determines the size of the change in disposable income or budget prompting responses from second-order consumers and producers. Here, several scenarios may arise depending on monetary savings and consumption patterns. Part of these savings encourage agents to make re-spending decisions. The indirect rebound effect causes an increase in resource usage by manufacturers via re-spending part of the saved energy to increase the production capacity [50]. The indirect rebound effect follows the same concept as the indirect effect in terms of input–output analysis in that shock changes an agent's budgeting, thus entailing re-spending decisions [23]. A proportional scenario is considered here for decisions inside an extended input–output (IO) energy model.

The IO analysis begins by considering that the production of an economy (x) can be expressed using the traditional Leontief [51] equation as follows:

$$x = (I - A)^{-1}\hat{A}\cdot f \tag{6}$$

where x is an n × 1 vector that shows the total production of all sectors of a given economy, I is the identity matrix with A being the n × n matrix of technical coefficients that indicates each sector's input for its own production and, finally, f is an n × 1 vector that refers to each sector's final demand. Changes in real income due to a decrease in the energy costs caused by (energy efficiency improvements) will modify vector f through re-spending. The matrix $(I\text{-}A)^{-1}$ is the inverse Leontief Matrix, which shows the requirements that are necessary to deal with the final demand.

The IO model enables the analysis of the linkage between the energy consumption, the production sectors and the final demand. To do so, both sides of Eq. (2) are pre-multiplied by means of matrix diagonalization of energy intensities($\widehat{E}$), with the sector of n × n dimension being calculated for each component as follows:

$$E_j = \frac{e_j}{X_j} \tag{7}$$

where e_j and X_j are the energy consumption and total production of each productive sector (where $j = 1 \ldots n$), respectively. Consequently, Eq. (7) shows the total energy consumption of productive sectors in what is known as an extended IO energy model:

$$e = \widehat{E}\cdot X = \widehat{E}\cdot(I - A)^{-1}\cdot f \tag{8}$$

With e being an n × 1 vector, it represents the energy consumption of each of the sectors necessary to satisfy the final demand.

The proportional scenario for re-spending decisions makes f change because of income and output effects of the shock to e. Final values for the elements in vector e will show the indirect rebound effect. At this point, it is worth noting that inter-sectoral relationships remain unchanged, so the economy-wide rebound effect did not increase.

3.1.4. The Structural Decomposition analysis approach to assess the economy-wide rebound effect

Energy efficiency improvements can raise the energy demand of the whole economic system because the decrease in the relative price of energy-intensive products will further increase their consumption. This can lead to more energy consumption (a third-order response), defined as the economy-wide rebound effect. Therefore, to calculate the economy-wide rebound effect, changes in inter-sectoral relationships must be allowed. This implies changes in the technical coefficient matrix and also in the inverse Leontief Matrix. Going back to Eq. (1), the framework of theoretical analysis is indicated below [16] and [20]. Energy consumption in year t and $t + 1$ is expressed as:

$$E_t = Y_t I_t;\ E_{t+1} = Y_{t+1} I_{t+1} \tag{9}$$

Technological progress may increase energy efficiency while reducing energy intensity, with which there is balance. As technical progress leads to changes in energy savings (ΔE_s), this amount is expressed as follows:

$$\Delta E_s = Y_{t+1}\cdot(I_t - I_{t+1}) = Y_{t+1}\cdot\Delta I \tag{10}$$

ΔI measures changes in energy intensity. These changes may be broken down into three factors: i) energy efficiency due to technical progress; ii) changes in inter-sectoral relationships; iii) changes in sector structure for this, see Eq. (19) below. If the effect of technical progress on energy intensity changes is defined as $\Delta I_{T,}$ then the technical effect parameter of energy intensity changes (δ) may be written as:

$$\delta = \frac{\Delta I_T}{\Delta I} \tag{11}$$

Thus, the amount of energy savings achieved through technical progress in year t + 1 is described as:

$$\Delta E_s = Y_{t+1}\cdot(I_t - I_{t+1})\cdot\delta_{t+1} \tag{12}$$

While technical progress brings energy savings, it also promotes economic growth. In the absence of a decoupling of economic growth and energy consumption, the former will cause more energy consumption. This increase in output is represented as:

$$\sigma_{t+1}(Y_{t+1} - Y_t) \tag{13}$$

with σ_{t+1} being the contribution rate of technological progress to economic growth in year $t + 1$. Then, further energy consumption for this part of the output growth is given as:

$$\Delta E_g = \sigma_{t+1}\cdot(Y_{t+1} - Y_t)\cdot I_t \tag{14}$$

In Eq. (14), economic output and energy intensity may be directly obtained or calculated based on statistical data. Going back to Eq. (5), the contribution of progress to economic growth is written as:

$$\sigma_t = \frac{A_t^*}{Y_t^*} = 1 - \alpha\frac{K_t^*}{Y_t^*} - \beta\frac{L_t^*}{Y_t^*} - \gamma\frac{E_t^*}{Y_t^*} \tag{15}$$

Then, the results of Eq. (15) into Eq. (13) are taken and the total rebound effect is calculated based on the technological advances in Spain by re-writing Eq. (1) as follows:

$$RE_{t+1} = \frac{\Delta E_g}{\Delta E_s} = \frac{\sigma_{t+1}(Y_{t+1} - Y_t)I_{t+1}}{Y_{t+1}(I_t - I_{t+1})\delta_{t+1}} \tag{16}$$

To deal with Eq. (16), the δ values still need to be assessed, which is what the Structural Decomposition Analysis does.

Going back to Eq. (8) and dividing it by the final demand vector f, we obtain:

$$\varepsilon = \frac{e}{f_t} = \widehat{E}\cdot(I - A)^{-1}\cdot\frac{f}{f_t} = \widehat{E}\cdot(I - A)^{-1}\cdot\varphi = \widehat{E}\cdot L\cdot\varphi \tag{17}$$

where ε is an n × 1 vector, with each of its elements being the sectoral energy consumption per unit of final demand. The total sum of these elements represents the total energy consumption of the economy per unit of final demand. It may be considered as a proxy for energy intensity. In Eq. (17), $\widehat{E}$ is the diagonalizable matrix of energy intensities, L is the Leontief inverse matrix and φ is an n × 1 vector with each of the elements being the ratio of sectoral final demand on the ultimate demand. It represents the share of ultimate demand of each and every institutional sector.

The Structural Decomposition Analysis approach allows changes in energy consumption per unit of final demand between two consecutives periods of time to be decomposed into factors as follows:

$$\Delta\varepsilon = \Delta\varepsilon_T + \Delta\varepsilon_L + \Delta\varepsilon_\varphi \tag{18}$$

with $\Delta\varepsilon_T$ being the *effect* on energy consumption per unit of final demand measuring the contribution of energy intensity when changes in inter-sectoral relationships remain balanced; $\Delta\varepsilon_L$ captures the *effect caused by changes in inter-sectoral relationships* showing the change in energy consumption per unit of final demand explained by inter-sectoral linkage (changes in intermediate goods and services consumption) after technological change, $\Delta\varepsilon_L$ corresponds to ΔI_T in Eq. (11). At this level, changes in inter-sectoral relationships are allowed. Finally, $\Delta\varepsilon_\varphi$ corresponds to the structure effect measuring the contribution of changes in the share of productive sectors on the final demand, thus explaining change in energy consumption per unit of final demand after full economic adjustment. In order to correctly assess the economy-wide rebound effect, both changes in inter-sectoral relationships ($\Delta\varepsilon_L$) and full adjustment of productive sectors after changes in energy prices caused by energy efficiency improvements ($\Delta\varepsilon_\varphi$) must be allowed. That is why $\Delta\varepsilon_{L+}\Delta\varepsilon_\varphi$ corresponds to ΔI_T in Eq. (11).

Each factor in Eq (18) is an n × 1 vector in which each element indicates its contribution to changes in energy consumption per unit of final demand between two consecutive periods under analysis. The sum of these elements shows the total change in energy consumption per unit of final demand. This total change could be due to the following changes in the decomposed factors:

$$\Delta\varepsilon_T = \Delta\widehat{E}\cdot L\cdot\varphi$$

$$\Delta\varepsilon_L = \widehat{E}\cdot\Delta L\cdot\varphi$$

$$\Delta\varepsilon_\varphi = \widehat{E}\cdot L\cdot\Delta\varphi \tag{19}$$

As an example, $\Delta\varepsilon_T$ shows the change in energy consumption per unit of final demand due to the energy intensity effect while the other effects remain in equilibrium; $\Delta\varepsilon_L$shows the change in energy consumption per unit of final demand due to changes in inter-sectoral relationships while the other effects remain in equilibrium. The most important difficulty when solving each expression of Eq. (19) is due to there being alternative methods to calculate the change between year 0 and T for each effect, depending on the reference year used, which could be year 0 or year T. Consequently, each decomposition effect could have alternative calculations and increase the difficulty of these calculations. The total number of possible decompositions is determined by $2^{n\hat{A}\cdot(n-1)}$. In our proposal, this implies 64 decompositions. However, not all of them are valid, as pointed out by Dietzenbacher and Los [52]. These authors showed that there are n! alternatives that are valid calculations for the decomposition effects. In our proposal, n is equal to three decomposition effects; therefore, the various calculations are reduced to 3! = 6.

Among the existing methods that can be used to calculate each effect, the arithmetical average of all the decompositions will be applied due to the small size of alternative valid calculations. A higher size calls for a method such as the one proposed by Seibel [53].

Finally, with $\Delta\varepsilon_L$ corresponding to ΔI_T in Eq. (11), this may be rewritten as:

$$\delta = \frac{\Delta I_T}{\Delta\varepsilon} = \frac{\Delta\varepsilon_L + \Delta\varepsilon_\varphi}{\Delta\varepsilon_T + \Delta\varepsilon_L + \Delta\varepsilon_\varphi} \tag{20}$$

Eq. (20) allows the δ values to be assessed for every two consecutive years of the period analyzed. The final step implies going back to Eq. (16) to assess total rebound effect values. Having obtained the direct rebound effect and indirect rebound effect values, the economy-wide rebound effect results are the residual value after subtracting the direct rebound effect and indirect rebound effect from the total rebound effect.

3.2. Materials

The estimation of the direct rebound effect, indirect rebound effect and economy-wide rebound effect is a complex process that involves the collection of data from several sources, as shown by the aforementioned methodology. Following the approach described above, the key necessary data can be summarized as: output data, capital stock information, labor data, energy balances and input–output tables.

The data used to adjust the production function referred to 2000–2015. Eurostat provided the GDP time series (Y_t) expressed in millions (10^6) of 2010 euros (M€) [54]. Capital stock information was taken from BBVA Foundation and Instituto Valenciano de Investigaciones Económicas [55], with values also measured in 2010 M€. Methodological data for capital stock information come from Pérez et al. [56].

Labor data (L_t) are from the Spanish Statistical Office (INE) measured as the number of employees. Energy consumption data measured in thousand tons of oil equivalents (ktoe) were taken from IDAE [57] and from Eurostat [58].

For the IO analysis, IOTs at 2014 basic prices [59] were used, which included 64 activity sectors. The last available year was 2014; thus, the full period under analysis corresponds to 2000–2014. To standardize the sectors included in the IOTs with those considered in the energy consumption data, they were grouped into 14 sectors as shown in Table A.1 in the supplementary materials. To assess δ values from Eq. (11), IOTs were taken from the WIOD database [60,61]. Table A.2 details the criteria for grouped activity branches.

Finally, the savings rate considered in the re-spending model was taken from Eurostat [54]. Table A.3 in supplementary materials details the savings rates for the whole period.

4. Results

4.1. Direct rebound effect

We initially planned to estimate Eq. (5) by Ordinary Least Squares regression, since the assumptions of normality and homoscedasticity of regression residuals are fulfilled and the Engle-Granger test confirms that the variables are co-integrated [62]. The results of this latter test are essential when working with time series in order to be able to apply the Ordinary Least Squares regression approach. If the Engle-Granger test indicates that the variables are co-integrated, as it does in this case, the estimation by means of Ordinary Least Squares regression captures stable, long-term relationships; in other words, it avoids spurious relationships. However, Eq. (5) has been estimated using a Ridge regression due to the multicollinearity problems presented by predictor variables, as confirmed by the VIF values.[3]

The Ridge regression minimizes the following expression:

[3] The test results conducted to estimate the Cobb Douglas production function are available as supplemental material.

$$\sum_{i=1}^{M}\left(Y_i-\widehat{Y}_i\right)^2=\sum_{i=1}^{M}\left(Y_i-\sum_{j=0}^{p}\beta_jX_{ij}\right)^2+\lambda\sum_{j=0}^{p}\beta_j^2 \tag{21}$$

where i corresponds to the number of years analyzed and j is the number of regressors (five in our case); λ is calculated using cross validation methods. The λ value indicates the weight given in the estimation to minimize the quadratic error and the penalty term, formed by the sum of the square of the coefficients. In this case, the Ridge regression yields better estimators than Ordinary Least Squares regression [48]. Eq. (22) shows the parameter values.

$$Y_t^*=(-7.3201+0.0043\times t)+0.1618K_t^*+0.5309L_t^*+0.1104E_t^* \tag{22}$$

An R^2 of 0.994 has been estimated; coefficients are all significant at 1% with an optimal λ of 0.0585.[4]

From Eq. (22), the size of direct rebound effect is calculated at 11.04% for the period considered. This means that 11.04% of available resources derived from energy consumption savings triggers additional energy consumption due to the reduction in its implicit price. The result for the direct rebound effect is in line with the findings reported by Allcott [64] for Illinois (10%), Barla et al. [65] for Canada (8%), Ito [66] for California (8.8%), Jessoe and Rapson [67] for Connecticut (12%) and Kulmer and Seebauer [68] for Austria (8–10%). These papers focused on developed countries as we do in this paper.

When assessing the rebound effect, Eq. (5) also provides estimates for each of the 14 productive sectors studied. To do so, sectoral values of σ were first estimated. However, the lack of data disaggregated by sector gave rise to results that were contrary to those indicated by the theoretical models, due to the stationarity of the energy consumption series in certain sectors and recession years within the period studied. For example, for the Agricultural, forestry and fishing sector, the estimation indicated that the increase in any of the production factors had a negative effect on economic growth. In other sectors, (transport and storage), none of the coefficients obtained were statistically significant.

4.2. Indirect rebound effect

The direct rebound effect determines the amount of disposable income or budget to be re-spent. In an IO model, this determines changes in the demand vector shock for economic activity. This shock causes the indirect rebound effect, which is captured through the extended IO energy model as described in Eq. (8). A new demand vector is calculated as follows: The IOT of Spain's domestic production up to 2014 was taken as the starting point. The final demand of institutional sectors (households and nonprofit entities, companies, public sector and foreign sector) was extracted from the IOT. From these results, and in relation to the size of the direct rebound effect, we determine the available resources for re-spending on goods and services (both domestic and imported) of each productive sector included in the IOT.

Since direct rebound effect was 11.04%, effective savings in energy consumption amounts to 88.96%. In general, this implies that a savings of 1% from energy efficiency improvements provokes an increase of 0.8896% in available resources to be re-spent on other goods and services. Further goods and services require new inputs for energy consumption. New energy requirements due to re-spending will determine the size of the indirect rebound effect.

To assess the size of the indirect rebound effect, two starting points are needed. The first is the value of final energy consumption for all productive sectors included in Spain's 2014 IOT. This was 72,023.8 ktoe. The second starting point is the initial spending of institutional sectors for their final demand, thus implying energy consumption.

[4] The statistical significance of each estimator has been calculated following Salmerón and Rodríguez [63]. The values obtained are shown in the supplemental material.

Table 1
Re-spend from energy consumption savings due to energy efficiency improvements (M €).

	Households + nonprofit entities	Capital investment by companies	Public consumption	Exports
Initial spending on energy consumption	29,356.8	1,594.6	5,686.1	3,509.2
Energy consumption savings	261.2	14.2	50.6	31.2
Additional spending in productive sectors other than energy sector	244.6	14.2	50.6	31.2

Table 1 shows figures for this second starting point.

As an example, take the household institutional sector (column 2 in Table 1). In this case, 1% additional savings would amount to 293.57 M€ when taking its initial spending as the starting point. Due to the direct rebound effect, 11.04% of these potential savings goes to additional spending, so new available resources for the household institutional sector due to energy efficiency improvements amounts to 261.2 M€ (88.96% of potential savings). For households, one needs to bear in mind that spending is not the only choice; savings is another. A savings rate of 6.34% [54] was assumed, so effective and additional spending is equal to 244.6 M€.

In order to assess the demand vector shock on the extended IO energy model, we need to know 1) how additional spending goes to every productive sector and 2) how to break it down between domestic spending and imports. After answering 1) and 2) it is also necessary to distribute additional spending in Table 1 into the various productive sectors. Table 2 shows how to do it by taking households and nonprofit entities as an example regarding the case of the Agriculture, forestry and fishing sector.

Households and nonprofit entities spend 1.7% of their additional budget, which means 4.1 M€ of their total new available resources (244.6 M€). Only 62.1% of additional spending goes to domestic goods and services; the rest of the new budget goes to imports. An amount of

Table 2
Households and nonprofit entities re-spending broken down by productive sectors (M€).

	(1)	(2)	(3)	(4)
Agriculture, forestry and fishing	1.7	4.1	62.1	2.6
Mining and quarrying	0.0	0.1	43.7	0.0
Food, beverages and tobacco	8.1	19.8	72.4	14.3
Textile and leather	2.3	5.7	22.6	1.3
Paper, pulp and printing	0.4	0.9	78.1	0.7
Chemical and petrochemical; non-metallic minerals	4.1	9.9	64.1	6.4
Basic metals and fabricated metal products	0.3	0.8	67.3	0.5
Machinery	0.9	2.2	31.2	0.7
Transport equipment	2.2	5.3	24.8	1.3
Other industries	0.9	2.2	35.6	0.8
Construction	1.0	2.4	99.1	2.4
Energy sector	3.8	9.3	99.6	9.3
Transport and storage	2.7	6.7	93.4	6.2
Commercial, services and public services	71.6	175.2	97.6	171.0
TOTAL	**100.0**	**244.6**	**88.9**	**217.4**

(1) Sectoral consumption as a share of total consumption (%).
(2) Increase in sectoral consumption due to energy efficiency improvements (M €).
(3) Sectoral domestic consumption as a share of total consumption (%).
(4) Increase in domestic consumption due to energy efficiency improvements (M €).

2.6 M€ corresponds to the re-spending of households and nonprofit entities on goods and services from the Agriculture, forestry and fishing sector. New goods and services will require additional energy consumption, thus determining the indirect rebound effect resulting from energy efficiency improvements, but only for households and nonprofit and the Agriculture, forestry and fishing sector, which are used here as an example.

For all other productive sectors included in the IOT, we proceeded in the same way. To simplify, it was assumed that company investment spending goes only to capital instead of capital and stock. Savings decisions were only contemplated for households, with this being a limitation for our research. Further research might consider savings scenarios for the public sector.

Table 3 shows the increase in demand caused by the re-spending of all institutional sectors. The last column exhibits the value of each element for the final demand. This vector was taken as the shock to the extended IO energy model to assess the size of the indirect rebound effect.

Indirect rebound effect values up to 2014 are shown in Table 4. As a whole, the indirect rebound effect implies an additional energy consumption of 13.2 ktoe. As expected, the energy sector shows a high value for increasing energy consumption, but the same is true for the Transport sector (6 ktoes)–almost half of the total increase—and the Commercial, services and public services (2 ktoes). Others sector with high values but in relative terms are Food, beverages and tobacco and Agriculture, forestry and fishing. Lower impacts correspond to Construction, Textile and leather, Mining and quarrying and Transport equipment.

Indirect rebound effect values in Table 4 expressed in percentages are derived from the energy consumption figure. As an initial spending value of 1% (for households and also for the rest of institutional sectors) was assumed, it corresponds to 720.2 ktep of energy consumption (a 1% share of total energy consumption in 2014; 72,023.8 ktep). Taking 720.2 ktep as the reference value, an increase in energy consumption of 13.2 ktep is due to energy efficiency improvements shares of 1.83%. This determines a total indirect rebound effect size of 1.83%.

Fig. 1 shows the indirect rebound effect trend for the entire period, in total values, and Fig. 2 shows it by sector. Table A.4 in the supplementary materials details all results in terms of ktoe. For the entire Spanish economy, the indirect rebound effect varies from 1.2% to 1.8%. An increase in this value appears from 2008 before stabilizing in 2012. This coincides with an extended period of energy-intensive behavior during recession years. Energy intensity may rise during periods of recession due to the decoupling of energy consumption and economic activity. Decreased production levels could provoke an increase in energy consumption per unit produced and a reduction in the use of productive capacities. The limited use of installed capacities and maintaining fixed consumption levels explains the increased consumption per production unit [35].

As expected, the energy sector shows high values for the indirect rebound effect. The same happens with the Commercial, services and public services and the Food, beverages and tobacco sectors. These three productive sectors show values from 1.3% up to 2.1%. As with the total indirect rebound effect size for Spain, an increase is detected from 2008 onwards. It should be borne in mind that the Kyoto Protocol came into force in 2005. Thus, it could be the case that the first results in terms of energy efficiency improvements began to appear after 2005, meaning that part of the available resources that sectors started to re-spend have higher values for the indirect rebound effect. The major recession of 2008 forced a strong indirect rebound effect to decrease for the most exposed productive sectors; namely, Construction, Transport equipment, Machinery and Other industries.

As discussed in the introduction section, the size of the rebound effect, regardless of its components, remains a matter of debate. Thus, it is informative to compare our results with other studies. Freire-González [11] assessed two measures for the indirect rebound effect caused by the behavior of Spanish households after energy efficiency improvements: both differ notably from our findings. When considering a direct rebound effect of 30%, the indirect rebound effect reported by this author was 34.60%, and 24.71% when taking a direct rebound effect size of 50%. He used 30% and 50% values for the direct rebound effect, as these were considered among the range of estimates found in the literature on the direct rebound effect in households for industrialized countries [12,69,70]. Values were determined by using price elasticities but not through a production function, as standard practice when analyzing productive sectors. Sorrell [13] and Freire-González [11] acknowledged that the price elasticities approach tends to overestimate the rebound effect.

Closer to our results, Thomas and Azevedo [71] found an indirect rebound effect of 10% for US households. These findings are of particular interest because these authors conducted their research following an IO approach, as we do, under the assumption of a 10% direct rebound effect (near 11.04% as we found) from an energy efficiency intervention which reduces household expenditures in either electricity, natural gas, or gasoline, and the US economic structure, energy prices, and electric grid mix of 2002. Recently, Fullerton and Ta [72] found an indirect

Table 3
Institutional sectors re-spending broken down by productive sectors (M€).

	(1)	(2)	(3)	(4)	TOTAL
Agriculture, forestry and fishing	2.6	0.1	0.0	1.2	3.9
Mining and quarrying	0.0	0.1	0.0	0.5	0.6
Food, beverages and tobacco	14.3	0.1	0.0	2.5	16.9
Textile and leather	1.3	0.0	0.0	1.4	2.7
Paper, pulp and printing	0.7	0.0	0.0	0.6	1.4
Chemical and petrochemical; non-metallic minerals	6.4	0.2	0.3	6.6	13.4
Basic metals and fabricated metal products	0.5	0.3	0.0	2.3	3.2
Machinery	0.7	0.5	0.0	2.4	3.6
Transport equipment	1.3	0.6	0.1	4.8	6.8
Other industries	0.8	0.3	0.0	0.5	1.6
Construction	2.4	5.9	0.2	0.2	8.8
Energy sector	9.3	0.1	1.1	0.3	10.7
Transport and storage	6.2	0.1	1.4	1.8	9.4
Commercial, services and public services	171.0	3.8	45.8	6.2	226.7
TOTAL	**217.4**	**12.0**	**49.0**	**31.2**	**309.7**

(1) Households and nonprofit institutions consumption. Household consumption and Non-profit institutions serving households.
(2) Investment spending in fixed capital.
(3) Public spending.
(4) Exports.

Table 4
Sectoral energy consumption after re-spending decisions (ktoe and %) and 2014 indirect rebound effect values.

Activity Branches	ktep	(% on total)	Indirect rebound effect
Agriculture, forestry and fishing	0.5	4.0	1.9
Mining and quarrying	0.0	0.3	0.8
Food, beverages and tobacco	0.5	3.7	2.1
Textile and leather	0.0	0.3	1.3
Paper, pulp and printing	0.4	3.0	1.7
Chemical and petrochemical; non-metallic minerals	1.0	7.6	1.4
Basic metals and fabricated metal products	0.4	3.1	1.1
Machinery	0.1	0.7	1.1
Transport equipment	0.0	0.3	1.0
Other industries	0.2	1.2	1.4
Construction	0.1	0.9	0.9
Energy sector	1.8	13.7	2.1
Transport and storage	6.0	45.6	1.9
Commercial, services and public services	2.0	15.5	2.3
TOTAL	**13.2**	**100**	**1.83**

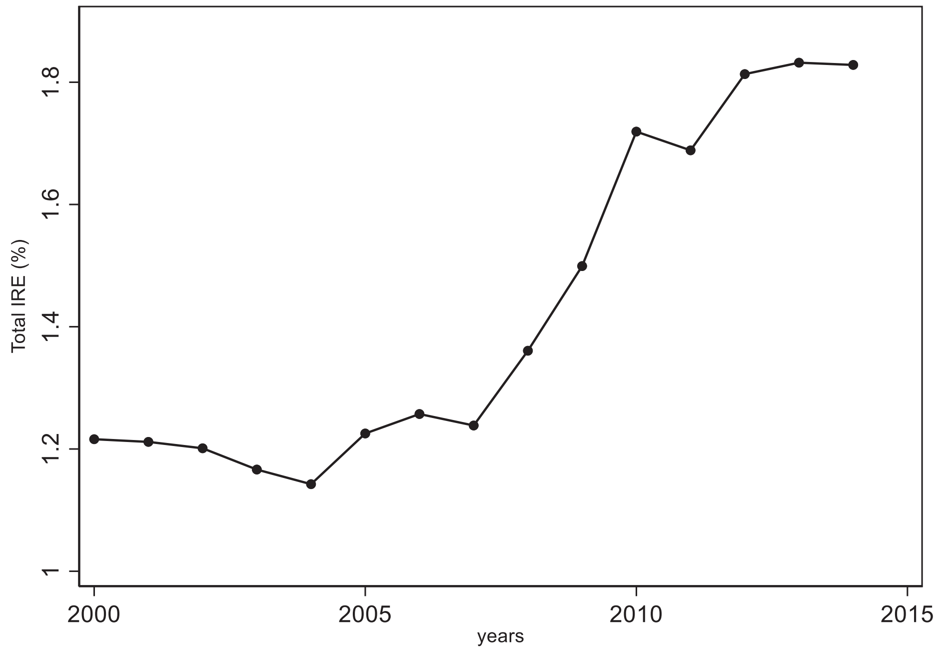

Fig. 1. Indirect rebound effect (IRE) total value for the Spanish economy % (2000–2014).

rebound effect of 4.26% from a costless technology shock when no policy measures are implemented to limit it. This result is quite similar to ours, although the cited authors did not deal with the economy-wide rebound effect assessment.

The literature pays attention to most of the productive sectors for which higher indirect rebound effect values were found; for example, the Transport sector, where the increase in ecommerce and logistic activities acts as a catalyst [73]. Llorca and Jamasb [1] found that the rebound effect for refrigerator transport in the EU-15 was 4% for 1992–2012, but without breaking down the rebound effect. The results from Craglia and Cullen [74] for the UK were similar (4.6%). Other industrial sectors have also received a good deal of scholarly attention [50,75,4]. An innovative analysis of the rebound effect in Agriculture is provided by Paul et al. [76] for the case of Germany.

4.3. The economy-wide rebound effect

The economy-wide rebound effect results are the residual value after having subtracted the direct rebound effect and indirect rebound effect from the total rebound effect. Table 5 presents the results obtained for δ and σ parameters in Eq. (16), for the entire period, and for the direct rebound effect, indirect rebound effect, economy-wide rebound effect and total rebound effect. Negative economy-wide rebound effect values imply that the re-weighting of energy-intensive sectors after reducing the energy price—full adjustment in the economy after changes in sectoral relationships—causes energy savings (a discussion regarding the positive and negative values of the rebound effect can be found in [72]. Negative values appear for two of the periods considered but do not outweigh the positive values for the direct rebound effect and indirect rebound effect. The economy-wide rebound effect varies from 4.51% to 128.45%. The higher value can be explained by the only two-year period when a backfire effect appears, in 2005–2006 (a backfire effect or Jevon's paradox happens when a rebound higher than 100% causes energy efficiency improvements to raise energy consumption [77,9,78]. However, compared with direct rebound effect and indirect rebound effect values, the economy-wide rebound effect does not show a clear trend for the period being considered (see Fig. 3), so despite the interesting information derived from breaking down the rebound effect into its components, we have to take the specific results for the economy-wide rebound effect with caution.

Any attempt to compare results for the economy-wide rebound effect with those in similar papers in the literature is complicated by the fact that few studies assess this specific type of rebound effect. The literature based on CGE models provides a global measure for the rebound effect after full economy adjustment; that is, including the effect on industrial relationships after the shock to energy prices from energy efficiency improvements. However, results from CGE do not break down the rebound effect into its components, so the size of the economy-wide rebound effect is not explicitly assessed. A recent paper conducting a general econometric equilibrium estimation failed to break down the rebound effect, but does find a high value for the economy-wide rebound effect after 4 years of energy efficiency improvements shock close to 100% [79]. For the economy of Spain, Guerra and Sancho [80] report an rebound effect varying from 87.4% to 90.8%; Arocena et al. [81] find a value higher than 70%; and Duarte Sánchez-Chóliz and Sarasa [82] estimate an rebound effect value of 55.85% up to 2030. Using a different approach to the CGE, Cansino et al. [77] coincide with the finding of this paper but do not find evidence to support Jevon's paradox for the Spanish economy. There are other papers not focused on Spain that also merit attention. In the case of Austria, the economy-wide rebound is 65% [68]. More broadly, it is possible to compare the economy-wide rebound effect with what Gillingham et al. [15] called a macroeconomic growth rebound effect. These authors recognized that compared with the direct rebound effect and indirect rebound effect, far less is known (or knowable) about the macroeconomic rebound. They do not expect the macroeconomic growth rebound effect to exceed 60%.

Recently, Stern [83] sought to determine how large the economy-wide rebound effect was. This author recognized that despite much research on this topic, there is not yet a definitive answer to the question.

4.4. Overall results

Regarding the size of the rebound effect as the overall result, the values in Table 5 show that restrictive energy policy measures in Spain are needed to control it. Table 5 shows values between 6.8% and 139.6% for the overall effect. When extreme values are eliminated, the rebound effect or the overall effect ranges between 10 and 50%, without showing a clear trend. The results confirm that a substantial part of the energy savings that could be gained from energy efficiency improvements is not

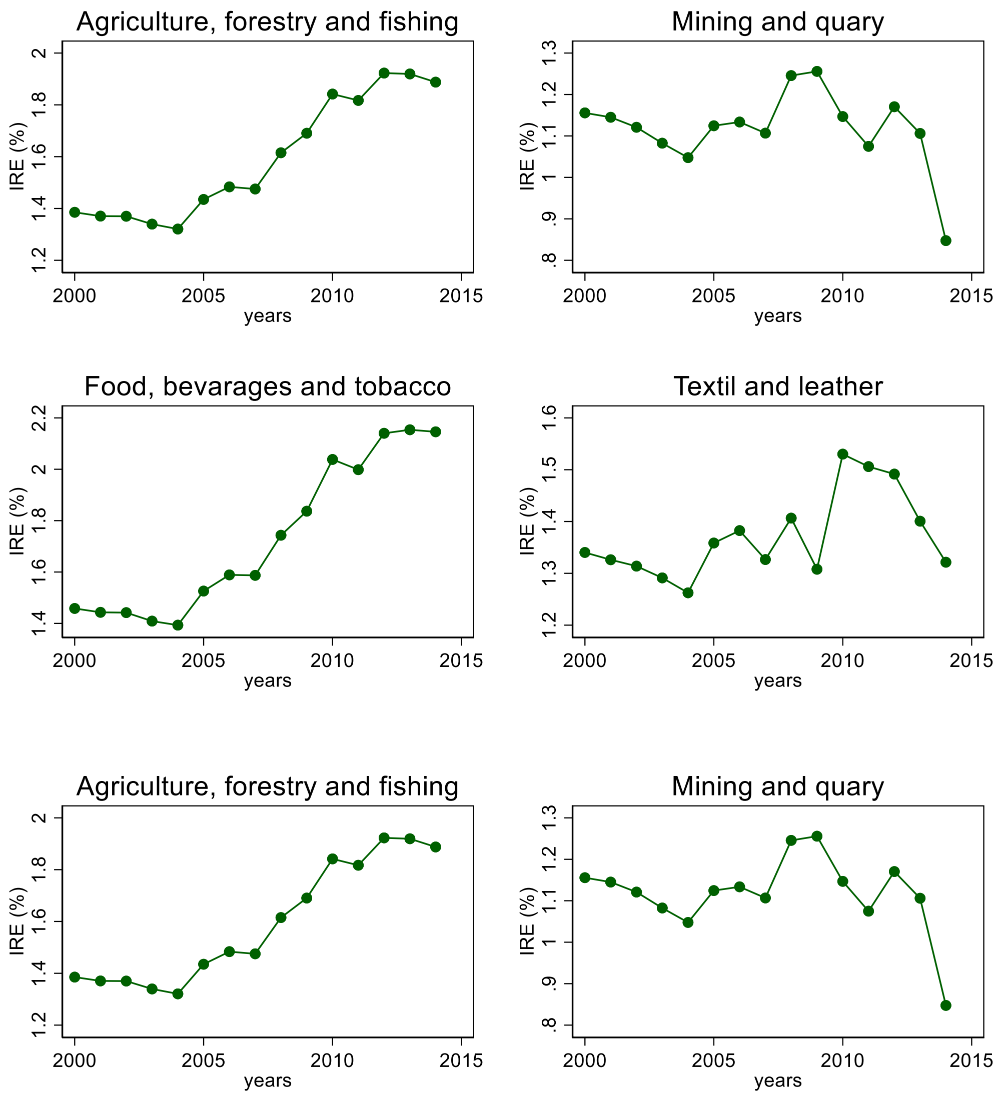

Fig. 2. Multisectoral values of the indirect rebound effect (IRE) for the Spanish economy % (2000–2014).

ultimately achieved due to the rebound effect.

For the total period analyzed, there are two results that merit particular attention. One corresponds to the years 2005–2006, showing a value greater than 100%. This indicates that the energy efficiency improvements led to an additional energy consumption 1.4 times higher than the savings. The explanation for this result lies in the high value of the economy-wide rebound effect. Other striking results correspond to the periods 2007–2008 and 2013–2014 (6.8% and 9.8%, respectively). In this case, we observe net energy savings stemming from energy efficiency improvements, with the economy-wide rebound effect also being negative.

The literature offers interesting evidence about how certain rebound effect-oriented measures have worked. Hybrid rebound effect policies rather than a single policy seem to be the appropriate way to control the rebound effect. Based on this evidence, utility-based programs (i.e., rebate programs with local utility company energy efficiency) could limit the consequences of the rebound effect by ensuring the independence of energy sources from the power sector (the sector showing the highest value for the indirect rebound effect). Careful use of energy price strategy is also worth exploring [84,85]. A penalization (or incentive) mechanism for energy consumption may also be helpful. Penalty mechanisms would be levied if additional energy consumption occurred due to the rebound effect, while incentive instruments (e.g., efficiency subsidies) would apply if the rebound effect did not appear. Raising consumer awareness regarding the consequences of the rebound effect and behavior changes would also be welcome measures (e.g., enhancing information offered through facility labeling; see [86], and [87].

However, if the technology is available and economic agents are restricted to buying more energy-efficient services and goods than they would if unconstrained, then an increase in required stringency could increase marginal costs and reduce real income. Before recommending such measures, the final impact on welfare must be considered by comparing cost and benefits derived from both energy efficiency improvements and any possible restrictions. The mandate could spark a positive or negative rebound, either of which could be associated with a net welfare gain or loss. Only if extra costs are justified by the benefits of reduced negative externalities from energy use could a restrictive measure be recommended from a welfare perspective.

5. Conclusions

This article seeks to delve deeper into the debate on the energy rebound effect caused by energy efficiency improvements, by breaking the effect down into its three components: the direct rebound effect, indirect rebound effect and economy-wide rebound effect. The ultimate goal and the novelty of this study is to break the overall rebound effect

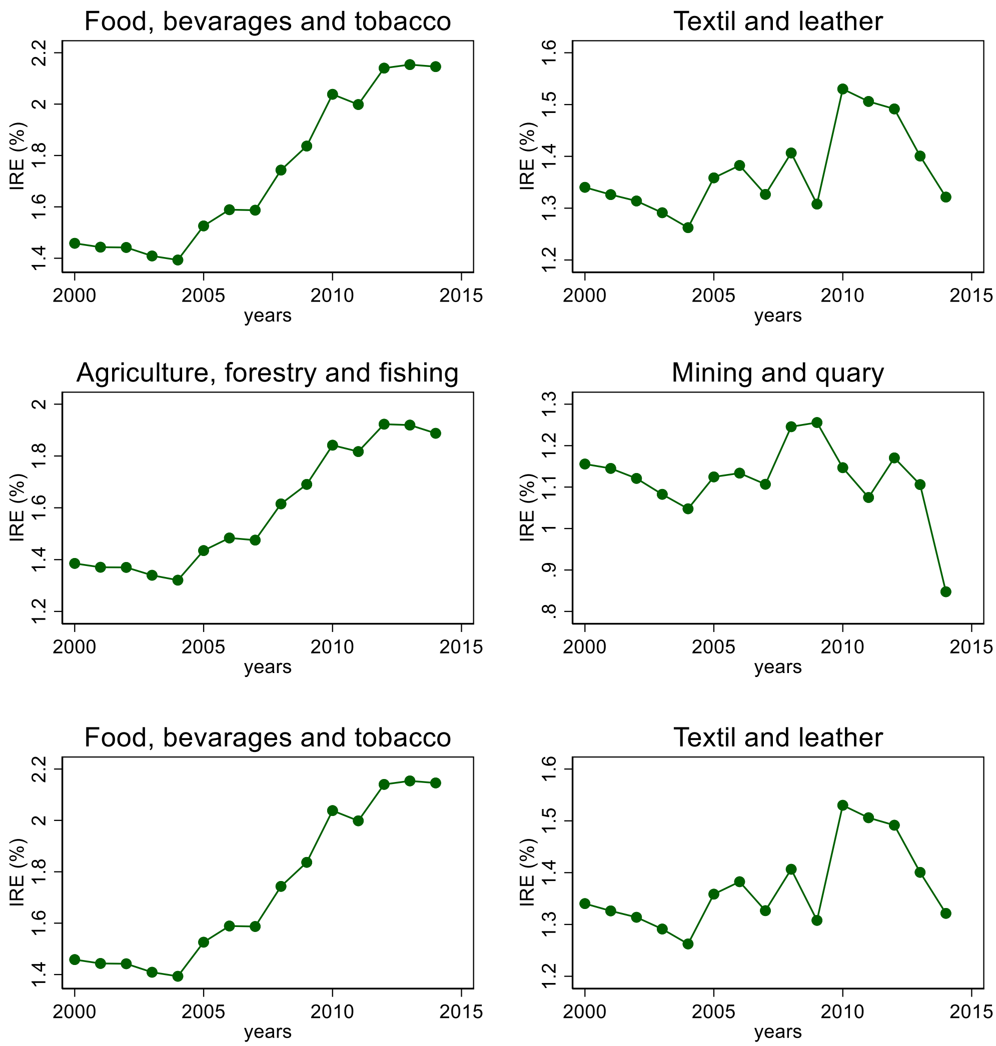

Fig. 2. (*continued*).

Table 5
Values for the rebound effect, direct rebound effect, indirect rebound effect and economy-wide rebound effect.

Years	σ	δ	Direct rebound effect (%)	Indirect rebound effect (%)	Economy-wide rebound effect (%)	Rebound effect (%)
2000–01	0.09851	0.8366	9.85	1.21	5.60	16.7
2001–02	0.09865	0.7924	9.87	1.20	41.04	52.1
2002–03	0.09872	0.3220	9.87	1.17	1.43	12.5
2003–04	0.09878	0.7802	9.88	1.14	24.49	35.5
2004–05	0.09885	0.2412	9.89	1.23	39.95	51.1
2005–06	0.09892	0.1872	9.89	1.26	128.45	139.6
2006–07	0.09900	0.1161	9.90	1.24	4.86	16.0
2007–08	0.09925	0.4131	9.93	1.36	−4.51	6.8
2008–09	0.09982	0.5835	9.98	1.50	10.96	22.4
2009–10	0.10015	0.4859	10.02	1.72	41.12	52.8
2010–11	0.10053	0.3557	10.05	1.69	22.56	34.3
2011–12	0.10097	0.2269	10.10	1.81	8.51	20.4
2012–13	0.10136	0.7997	10.14	1.83	38.42	50.4
2013–14	0.10161	0.2841	10.16	1.83	−2.15	9.8

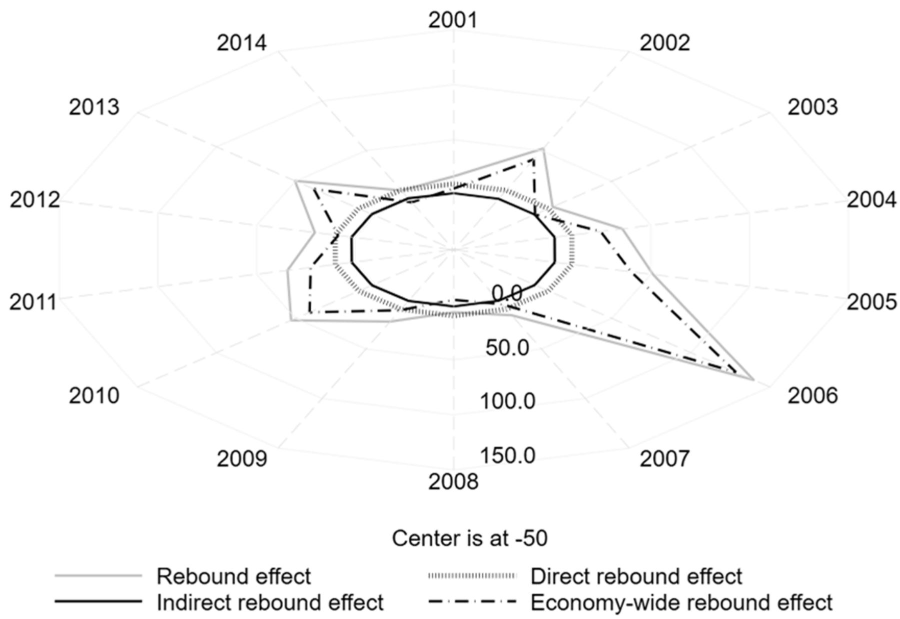

Fig. 3. Rebound effect, direct rebound effect, indirect rebound effect and economy-wide rebound effect values for the Spanish economy % (2000–2014).

down by combining the Cobb-Douglas production function and decomposition techniques. The implication of replacing the LMDI I with Structural Decomposition Analysis is that while the latter allows full adjustments through inter-sectoral relationships, the former does not. The key issue lies in the use of Input-Output tables. The changes from year to year due to changes in the technical coefficients matrix are at the core of the Leontief model's ability to capture the third-order response.

The methodological contribution which involves assessing the components of the rebound effect help fill the gap caused by a lack of consensus on measurement. This contribution is useful in that it can help to create an appropriate roadmap for tangible policy actions and also to properly evaluate the implications of energy efficiency policies on welfare.

Major findings indicate that the total rebound effect varies from nearly to 10% to around 50%. Only in two periods do values move away from the average. When breaking down the rebound effect, the part explained by the direct rebound effect is around 10%; the related findings in the literature are in line with this value. The indirect rebound effect is a small part of the total rebound effect, registering values of between 1.2% and 1.8% (higher values for the Energy sector, lower for Construction and Transport equipment). The recession period generated an increase in the indirect rebound effect, which is supported by the literature. From a sectoral perspective, the rebound effect should be controlled in both the energy and transport sectors. From the discussion throughout the paper, we can suggest specific policy measures oriented towards limiting the rebound effect in those sectors examined in the analysis. However, before recommending restrictions on economic agents' decisions, their impact on welfare must be estimated. Finally, the economy-wide rebound effect varies from −4.51% to 128.45%, without showing a clear trend for the period considered, so the results obtained should be taken with caution.

Of course, the literature remains inconclusive, but we should not ignore the fact that the total rebound effect has various components that need to be properly assessed. Our particular approach opens up a series of research lines for future studies. The assumption that company investment spending goes only to capital instead of capital and stock is a limitation of our research. Further research might consider savings scenarios for companies and the public sector. A welfare analysis focused on adequate policy measures to reduce the size of the rebound effect will enrich the research on this topic.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2021.117961.

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