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Do Spanish energy efficiency actions trigger JEVON'S paradox?

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ABSTRACT

This paper explores whether the changes in energy intensity in Spain have led to improvements in the energy consumption levels or to a backfire effect offsetting the expected decrease. Jevon's paradox or backfire effect happens when a rebound higher than 100% causes energy efficiency improvement to raise energy consumption. To test Jevon's paradox or the backfire effect caused by energy efficiency actions, a Logarithmic Mean Divisia Index I (LMDI-I) is used for the Spanish economy. The period under consideration ranges from 2000 to 2015, when three national action plans were implemented. The main methodological novelty of this paper consists on to block the economic activity effect in a second decomposition round to better explore the effect of energy efficiency on energy consumption. As a whole, our results do not support Jevon's paradox for the sectors analyzed. However, they do warn about a possible backfire effect in the industry, transport and service sectors. Major findings follow these same findings when the activity effect is blocked.

1. Introduction

Energy efficiency has become a primary energy policy goal in many countries conditioning their policies towards energy-intensive sectors [1–3]. However, Energy Efficiency Improvements (EEI) could lead to changes in the demand for energy services that offset some of the achieved energy savings in the form of rebound effects. Rebound effect has been defined as the additional energy consumption from overall changes in demand as a result of behavioral and other systemic responses to EEIs [4–7].

The idea of the energy rebound effect dates back to 1865; literature also refers to the rebound effect as "Jevons' Paradox" whereby a technology that enhances efficiency does not necessarily lead to less consumption of that resource [8]. The first to study this rebound effect phenomenon in the form of economic literature were Brookes & Khazzoom, thus, the "Jevons' Paradox" is also known as the "Khazzoom–Brookes" Postulate [9,10].

[11,12] identified three types of rebound effects. These are direct rebound–affecting the energy consumption of the energy service affected by the energy efficiency improvement, indirect rebound effect–affecting other goods, services and areas and economy-wide effects which go even further, and affect prices, quantities and produce global economic readjustments.

This paper focus on testing Jevon's paradox or Khazzoom–Brookes Postulate for Spain's economy, when this is conceived as a backfire effect caused by energy efficiency actions. The reason why Spain has been chosen is due to its highest energy intensity when is compared to the average of the rest of European Union's Member States. Concretely, in 2008, Spanish energy intensity level was 19% upper the EU-15 average [13,14]. Since then, the Spanish Government has implemented several energy efficiency plans in order to reduce energy intensity. The period under consideration in this research is 2000–2015 and contains three national energy efficiency action plans. The last one includes mandatory actions established by Ref. [15]; which implies a 20% saving on energy consumption levels up to 2020. Most of the measures included in Spain's plans of action are based on technological improvements and are energy intensity oriented. These plans covered the periods 2005–2007, 2008–2012, 2011–2020 (updated after [15] for the period 2014–2020) [16–19]. An in-depth analysis of Spain's Spanish plans of action, including detailed information about measures in force, is due to Román-Collado & Sanz [20].

Although many papers do not differentiate between types of rebound effect, whether direct or indirect effects, they are easily recognizable. Following Vivanco et al., [21]; an example of the rebound effect is defined as the way in which fuel efficiency improvements in passenger cars have made driving cheaper, thus

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resulting in users driving more and buying larger cars (direct effect) and/or spending the remaining savings on other products (indirect effect). As a result, total fuel and energy savings are reduced. In the latter case, a backfire effect is defined as a rebound higher than 100% which implies energy efficiency improvement acting on energy intensity that does not reduce but rather increase energy consumption [9].

To test Jevon's paradox or the backfire effect on energy consumption caused by energy efficiency actions, a Logarithmic Mean Divisia Index I (LMDI-I) is used. Five decomposition factors were considered: population, economic activity, economic structure, energy intensity and energy resource mix. Conducted analysis is a multisectoral one, including the six sectors where Spain's national plans were focused (agriculture, industry, energy, transport, services and residential). Five types of fuels were considered for the energy resource mix (oil, gas, renewable energy sources, electricity and solid fuels). This research uses a valuable paper by Inglesi-Lotz [22] as the start point, to then go further. The aim of this paper is not to estimate the precise rebound effect caused by the implemented energy efficiency measures but to decompose the determinants of energy consumption changes in Spain from the backfire effect perspective. What can be derived from the results herein is whether the changes in energy intensity have led to improvements in the energy consumption levels or to a backfire, the effects of which have managed to offset the expected decrease in energy consumption with improvements in energy intensity. The first contribution of this paper to the literature is from a methodological perspective. Concretely, the methodological approach implemented has allowed us to block the economic activity effect in a second decomposition round to better explore the effect of energy efficiency on energy consumption. The theoretical support for this second-round decomposition is that EEI does not act in a partial equilibrium scenario where all remains equal. Changes in population or in the energy resource matrix happen at the same time as EEI. In fact, the energy rebound effect indicates that technological progress not only improves energy efficiency, but also promotes economic growth, therefore raising the demand for energy; so it is interesting to block the effect of economic growth on energy consumption to observe whether Jevon's paradox occurs or not. The conducted research also contributed to bridge the literature's gap being the first in testing Jevon's paradox (or Khazzoom–Brookes Postulate) for Spanish economy from a multisectoral and expost perspective and through an ex post analysis.

The rest of the paper is organized as follows; Section 2 offers a review of the various approaches revolving around rebound effect in the literature. Section 3 exposes methodological approach developed in the paper. Dataset is detailed in Section 4, while the results obtained are presented in Section 5. Section 6 offers the conclusions reached.

2. Literature review

There is a broad list of methodological approaches to assess the rebound effect.

Computable general equilibrium (CGE) models have been widely used to capture the economy-wide rebound effect providing exante analysis. Turner [23] used a CGE framework to investigate the conditions under which rebound effects may occur in response to increases in energy efficiency in the UK national economy. Allan et al. [24] and Hanley et al. [25] worked with a similar approach. Turner & Hanley [26] used a CGE model of the Scottish economy to consider the factors influencing the 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. The paper by Yu et al. [27], must be also cited. It is also the case of Broberg et al. [28] assessing the economic wide rebound effect for the industry sector in Sweden. More recently, Bye et al. [29] used a multi-sector CGE of the Norwegian economy to explore the cost, emission and energy rebound effects of alternative interpretations of the policy underlying the proposed 2030 energy efficiency goal. Grepperud, & Rasmussen [30] also used a CGE approach for the Norwegian economy. A CGE based analysis for the Spanish case is due to Guerra & Sancho [31].

An econometric approach also shows intensive use in expost analysis. Berkhout et al. [32] might be cited as one of the reference paper. De Borger et al. [33] estimated an energy demand model in first differences to assess the rebound effect's magnitude in YRDUA's industrial sectors using dynamic ordinary least squares and seemingly unrelated regression methods. Llorca & Jamasb [1] analyzed the energy efficiency and rebound effects for road freight transport in 15 European countries during the 1992–2012 period using a stochastic frontier analysis approach and examined the influence of key features of rebound effect in the road freight transport sector. Freire-González [34] developed a hybrid methodology that combines econometric estimates, environmental extended input-output analysis and re-spending models that have been developed. As a part of this econometric approach, total factor productivity (TFP) is usually the way to represent the contribution of technological progress. The Cobb-Douglas and CES production function is employed to estimate total factor productivity.

Hediger et al. [35] linked econometrics with the emerging topic of Behavioral Economics by researching how households respond to efficiency improvements in their heating system. Not so far from Behavioral Economics, Santarius & Soland [36] exposed the existing rebound discourse to psychological theories.

Finally, analysis based on Index Decomposition Analysis (IDA) either in Structural Decomposition Analysis (SDA) as in LMDI version may be found in Alcántara et al. [37]; Cansino et al. [38]–for SDA–Cansino et al. [39]; Lin et al. [40]; Wang et al. [41]; Lin & Liu [42]; Inglesi-Lotz [22,43] for LMDI. Román-Collado & Colinet [44] is the most accurate and recent decomposition of energy consumption in Spain from a LMDI approach. Those are expost analysis.

3. Methodology

The LMDI-I decomposition model belongs to IDA family. It is a useful tool because of its theoretical support and feasibility. It satisfies relevant properties [45–47]. LMDI-I is complete in decomposition and consistent in aggregation while at the same time excellent in handling zero values [48–50]. Ang & Liu [51] and Ang & Choi [52] analyzed and proposed that the best way to handle it is by substituting zeros for a δ value between 10^{-10} and 10^{-20}. Ang & Liu [51] also showed that this strategy is robust when an appropriate value is used, and that it provides satisfactory results even for highly extreme cases. Upon comparing various index decomposition analysis methods, Ang [45] concluded that the LMDI method to be the most effective.

To analysis whether energy intensity improvements caused the backfired effect on Spain's energy consumption at the sectoral level i, Eq [1] decomposes its energy consumption (E_i) as follows,

$$E_i = \sum_{j=1}^{n} P \cdot \frac{Q}{P} \cdot \frac{Q_i}{Q} \cdot \frac{E_i}{Q_i} \cdot \frac{E_{ij}}{E_i} = \sum_{j=1}^{n} P \cdot A \cdot S_i \cdot I_i \cdot M_{ij} \qquad (1)$$

where n is the number of final energy sources, E_i the energy consumption of sector i, P the population, Q is the proxy variable that measures total output of the economy through the Gross Value Added (GVA), Q_i is the GVA of sector i. Finally, E_{ij} measures the energy consumption of sector *i* from the *j-th* energy source. LMDI-I model does not present interactions between the variables but rather their relative contributions to the change of the energy consumption over time.

From [1], the LMDI-I analysis allows the decomposition of changes in the energy consumption of sector *i*, between period t and t-1 (ΔE_i) for each energy source included in Spain's energy matrix [45,48,53]. In its additive formulation, decomposition is carried out on five factors or effects as shown by the following expression:

$$\Delta E_i = E_{i(t)} - E_{i(t-1)} = \Delta P^i + \Delta A^i + \Delta S^i + \Delta I^i + \Delta M^i \quad (2)$$

When an effect takes positive values, it acts as a driver of energy consumption; when values turn negative, then the effects act as a compensating factor of energy consumption. The definition of each factor is as follows:

a) ΔP^i: Population effect. It reflects part of the variation in sectoral energy consumption due to population changes. It acts as a proxy for the country's energy demand.
b) ΔA^i: Activity effect. Shows variations in sectoral energy consumption explained by changes in per capita income.
c) ΔS^i: Structure effect. It captures variations in sectoral energy consumption due to changes in the relative weight of sectors in production.
d) ΔI^i: Intensity effect. It measures variations in energy consumption due to changes in the sectoral energy intensity; that is to say, due to a change in energy consumption per produced unit of each sector between period t and t-1. Being that this is the key decomposition factor for the aim of the paper, in-depth details are provided below.
e) ΔM^i: Energy mix effect. Measures the contribution of the penetration of clean energy in the variation of final energy consumption.

Each effect can be calculated as follows:

$$\Delta P^i = \sum_{j=1}^{n} \omega_{ij} \ln \frac{P_{(t)}}{P_{(t-1)}} \quad (3)$$

$$\Delta A^i = \sum_{j=1}^{n} \omega_{ij} \ln \frac{A_{(t)}}{A_{(t-1)}} \quad (4)$$

$$\Delta S^i = \sum_{j=1}^{n} \omega_{ij} ln \frac{S_{i(t)}}{S_{i(\ t-1)}} \quad (5)$$

$$\Delta I^i = \sum_{j=1}^{n} \omega_{ij} ln \ \frac{I_{i(t)}}{I_{i(\ t-1)}} \quad (6)$$

$$\Delta M^i = \sum_{j=1}^{n} \omega_{ij} ln \frac{e_{ij(t)}}{e_{ij(\ t-1)}} \quad (7)$$

When applying the Mean Value Theorem, ω_{ij} corresponds to the weighting factor for the calculation of different effects and is obtained from the logarithmic mean, which considers the variation between two periods of sectoral energy consumption by energy source *j* according to [8]:

$$\omega_{ij} = \frac{E_{ij(t)} - E_{ij(t-1)}}{lnE_{ij(t)} - lnE_{ij(t-1)}} \quad (8)$$

Sign and magnitude of ΔI^i states whether changes in energy intensity have led to improvements in the energy consumption levels or, on the other hand, if the backfire effect has managed to offset the expected decrease in energy consumption with improvements in energy intensity. In other words, it represents if energy intensity decline leads to energy consumption increase or the contrary. As most of the changes in energy intensity specified in Spain's plans come from technological improvements, ΔI^i is the proxy for technological change. However, following [43] and Chertow [54]; caution must be used with this decomposition factor. These authors recognize that there is little social theory to suggest how to specify and measure technological improvements. Chertow [54] states: “Conceptually as well as numerically, P, population, and A, defined as a per capita measure of wealth, consumption, or production, have generally been more accessible to researchers than the technological improvements term.” Without ignoring this limit, from the ΔI^i sign and value, we derive whether the changes in energy intensity provoked backfire effect or not in energy consumption.

Going beyond previous research, it is essential to take into account that energy intensity improvements do not all remain equal. In fact, as technological progress not only improves energy efficiency but also promotes economic growth, the activity effect (ΔA^i) on energy consumption is partially due to the indirect rebound effect [21]. Therefore, a methodological development of LMDI to block the activity effect on energy consumption would give us finer information about whether the changes in energy intensity have led to improvements in energy consumption levels or to a backfire effect. To explore the, we have proceeded as follows.

From [2], a second decomposition of the energy consumption allows us to know the impact of the improvement in the energy intensity once the activity effect is blocked [41,55–57]. To do that, it is assumes that economic growth causes energy consumption. Now ΔEE_i is defined as the difference between changes in energy consumption for sector *i* and the activity effect

$$\Delta EE_i = \Delta E_i - \Delta A^i = \Delta P^i + \Delta S^i + \Delta I^i + \Delta M^i \quad (9)$$

Rewriting Eq (9) γ^i_{INT} in Eq (10) lets us calculate whether the changes in energy intensity causes a direct backfire effect on energy consumption between period t and t-1 once indirect backfire effect through economic activity changes is blocked.

$$\gamma^i_{TOTAL} = -\frac{\Delta EE_i}{\Delta A^i} = -\frac{\Delta P^i}{\Delta A^i} - \frac{\Delta S^i}{\Delta A^i} - \frac{\Delta I^i}{\Delta A^i} - \frac{\Delta M^i}{\Delta A^i} = \gamma^i_P + \gamma^i_{EST} + \gamma^i_{INT} + \gamma^i_{MIX} \quad (10)$$

As it is also possible that negative economic growth causes a decrease in energy consumption Diakoulaki & Mandaraka [56] rewrite Eq (10) as follows

$$\beta^i_{TOTAL} = \frac{\Delta EE_i - \Delta A^i}{\Delta A^i} = \frac{\left(\Delta P^i + \Delta S^i + \Delta I^i + \Delta M^i\right) - \Delta A^i}{\Delta A^i} \quad (11)$$

$$\beta^i_{TOTAL} = \frac{\Delta P^i}{\Delta A^i} + \frac{\Delta S^i}{\Delta A^i} + \frac{\Delta I^i}{\Delta A^i} + \frac{\Delta M^i}{\Delta A^i} - \frac{\Delta A^i}{\Delta A^i} = \beta^i_P + \beta^i_{EST} + \beta^i_{INT} + \beta^i_{MIX} - 1 \quad (12)$$

Eqs (10) and (12) give useful information regarding [15]. The reason is that this legal instrument promotes decoupling between energy consumption and economic growth. Eqs (10) and (12) show the energy consumption changes only attributed to the population, structural and intensity effects, excluding those provoked by the activity effect (where indirect rebound effect is embodied). Both indices measure the efforts that have been made in order to reduce energy consumption when the activity effect is blocked [56,58]. The interpretation of the results for both indices are the same.

This let us to test if the changes in energy intensity causes a direct backfire effect once indirect backfire effect is blocked. In fact, γ^i_{TOTAL} in Eq (10) and β^i_{TOTAL} (12) are a finest decoupling index between energy consumption and economic activity while γ^i_P, γ^i_{EST}, γ^i_{INT} and γ^i_{MIX} (also β^i_P, β^i_{EST}, β^i_{INT} and β^i_{MIX}) act as partial decomposition index for population, economic structure, energy intensity and energy sources mix effects.

Understanding γ^i_{TOTAL} and β^i_{TOTAL} when ≥ 1 expresses strong decoupling efforts implies that sectoral energy consumption decreases at the same time that the economy grows. Assuming that γ and β have the same meaning, if $0 < \gamma^i_{TOTAL} < 1$ then it expresses weak decoupling efforts, so that the inhibiting effect of sectoral energy consumption is weaker than the effect of economic growth; thus, sectoral energy consumption grows together with the economy. Finally, if $\gamma^i_{TOTAL} \leq 0$, it expresses that there were no decoupling efforts [56,58,59].

According to Roinioti & Koroneos [58] values higher than 0 for γ^i_{INT} (also for γ^i_P, γ^i_{EST} and γ^i_{MIX}) imply that energy intensity improvements do not causes direct backfire effect on energy consumption. Negative values advise a direct backfire effect. In order to simplify only γ notation is used when showing results.

4. Dataset

The sectoral energy consumption data measured in kilo tons of oil equivalent (Ktoe) come from the Energy Balances published by Eurostat [60]. The GVA data series, expressed in millions of euros at constant prices, was built up from the statistical series for the sectorial GVA at current prices and the chained volume indexes, published by the National Institute of Statistics (INE for the Spanish acronym). The base year is 2010. The figures for the population for the years 2000–2015 were also obtained from the INE [61,62].

The data for the energy transformation sector does not include the transportation and distribution of energy. The reason for this is that only in the last National Energy Efficiency Plan does the sector include these activities. In the previous plans, it was not included. For the inclusion of the residential sector in the analysis, the activities realized in households have been taken as a proxy. The correspondence of the sectors analyzed, national accounts and energy balances are detailed in Table A1 in annex.

The energy sources included in the energy mix factor are solid fuels, oil, gas, renewables and electricity. Offered Table A2 in the annex provides detailed information about its distribution by sectors.

5. Results

In Jevon's meaning, rebound effect reflects an individual person or group's behavioral inclination which should be stable for a while. However, obtained results show that the "rebound effect" fluctuates quite frequently-sometime it is negative while soon after it is positive. This is due to Jevons focused in England's consumption of coal after James Watt introduced the Watt steam engine, that means just one (although crucial) energy efficiency improvement. Currently, more than 3 million patent applications were filed worldwide [63]. Given this high number, when patents are incorporated as technological innovations to the productive processes it is expected that not all of them modify the behavior of the agents in the same direction. The index developed in this research captures the average effect on energy consumption for each of the sectors considered and for each of the years under analysis. The fluctuations respond to the high number of technological innovations and to the different reactions of the agents when they are incorporated into the productive activity.

5.1. First decomposition

From a sectoral perspective, the results from first decomposition analysis advise against Jevon's paradox or backfire effect in the

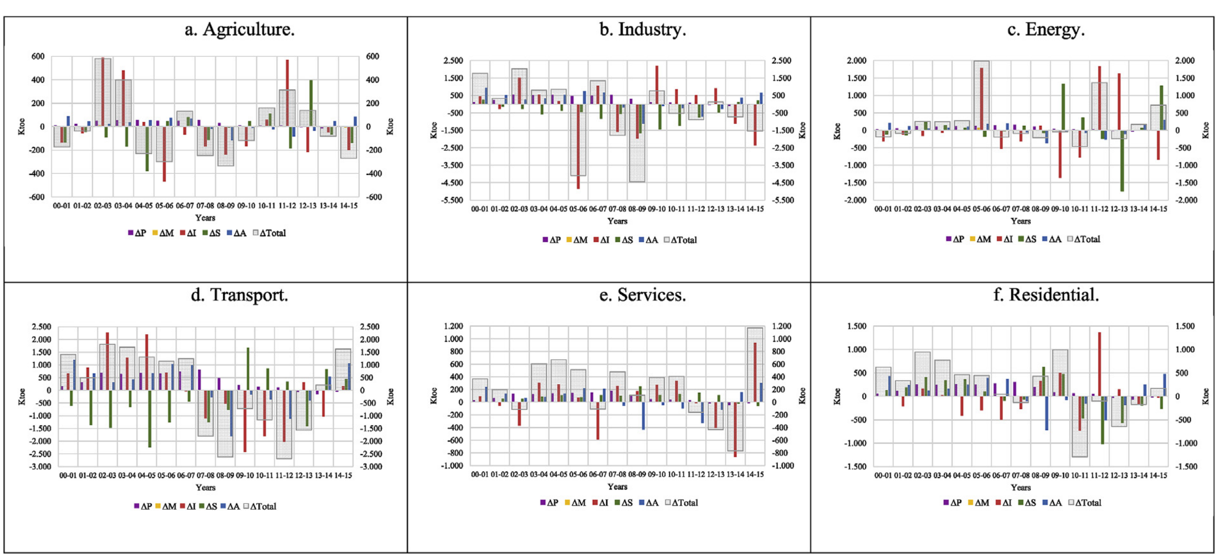

Fig. 1. Sectorial decomposition analysis.
Source: Own elaboration.

agriculture sector (Fig. 1a). For most of the years under consideration, the energy efficiency effect showed high and negative values. The only exceptions corresponded to sub-period 2000–2005 and 2010–2012. The net effect derived from technological improvements help reduce energy consumption in this sector. On the other hand, the economic activity effect (partly caused by indirect rebound effect) acted as a driver of sectoral energy consumption. Behavior as a driver turned to an inhibitor role only for economic recession period 2007–2013. The results obtained are in line with Arocena et al. [13] using a CGE approach. They found a rebound effect around 30% (far from a backfire effect) for the four types of fuels considered (coal, refined oil, electricity and gas).

As we do no develop a partial equilibrium analysis, LMDI's results show that other effects have to be considered when decomposing energy consumption changes. For example, population acted as a driver of energy consumption until demographic changes in 2012 when massive migrated people decided to go back to their countries of origin due to the economic crisis. The mix resource matrix effect also acted as an inhibitor and structure effect, but failed to show a clear pattern.

Evidence of a possible backfire effect appeared in the industry sector (Fig. 1b) with the energy efficiency effect showing positive values in nine of the fifteen years under study. However, literature explains that when there is an economic crisis, energy intensity has difficulties in adjusting [38] and 2018). This is due fixed energy consumption levels decoupled from a number of output units (for example, to illuminate factories independently of their activity). Together with this, economic activity and population effects acted as with the agricultural sector while structure effects inhibited energy consumption for most of the years.

Our findings are similar than those provided by Guerra and Sancho [31] but for the Spanish economy as a whole. The estimated a rebound effect in a range between 87.4% and 90.8%. The results obtained are also in line with Arocena et al. [13]. They found a rebound effect higher than 70% (close from a backfire effect).

A possible backfire effect is rejected upon analyzing the energy sector (Fig. 1c). For the same period, population and economic activity effects acted as in the agriculture and industry sectors. On the contrary, the energy resource matrix effect showed an economy moving slowly to a cleaner energy resource matrix. Structure effect showed an erratic behavior. Arocena et al. [13] found evidence also rejecting possible backfire effect in the energy sector with rebound effect's values around 65%.

Transportation was another sector advising of a possible backfire effect, but not for economic crisis years (Fig. 1d). The explanation provided by Vivanco et al. [21] is useful here because these authors wrote that fuel efficiency improvements in passenger cars have made driving cheaper, resulting in users driving more and purchasing larger cars (direct effect) and/or spending the remaining savings on other products (indirect effect). Economic activity and population effects acted as in the previous sectors, while structure effect inhibited energy consumption for most of the years. The last is due to a decrease in logistic activity because of economic recession. For this sector, our results are not similar to those obtained by Arocena et al. [13] but are close to those obtained by Guerra and Sancho [31] for the Spanish economy as a whole.

The heterogeneity of the service sector could explain the unclear pattern of energy efficiency; the effect differed from one economic activity to another while and the effects of population acted as usual (Fig. 1e). Here, the structure effect drove energy consumption.

Finally, the energy intensity effect rejects the backfire effect for the residential sector (Fig. 1f). Higher levels of household automation or smart use of domestic devices could explain this fact (Cansino et al., 2018). The same may be said for population and economic activity, while the energy resource matrix demonstrated a low use of clean energy in residential sector. Here our results are similar to those shown by Freire-Gonzalez [64] for Catalonia's region (in the northeast of Spain) that was a rebound effect between 35% and 49% and by Freire-Gonzalez [65] finding a rebound effect between 64.60% and 74.71% for the Spanish case.

5.2. Second level decomposition

The methodological approach developed offers valuable information from results obtained in a second level decomposition analysis when blocking the activity effect. Results for γ^i_{INT} in Eqs (10) and (12) inform whether the changes in energy intensity have a direct backfire effect on energy consumption once the indirect backfire effect through economic activity changes is blocked.

Table 1 includes major results regarding the direct effect on the energy intensity effect from a sectoral point of view. Table A.4 in annex provide detailed results. Regarding the agriculture sector, once the activity effect on energy consumption is blocked, the energy intensity effect takes on positive values that are higher than the one for most of the years. Once again, the economic crisis period is the only exception. In general terms, the agriculture sector seems to move to decouple economic growth from energy consumption. Table 2 lists the coupling/decoupling status for every of the considered sectors.

In terms of the industry sector, the direct effect of energy

Table 1
Years appearing direct backfire effect caused by energy efficiency.

Years	Agriculture	Industry	Energy	Transport	Services	Residential
2000–2001		+		+	+	
2001–2002				+		
2002–2003		+		+		+
2003–2004	+	+		+	+	+
2004–2005	+	+		+	+	
2005–2006	+	+	+	+	+	
2006–2007		+				
2007–2008					+	
2008–2009			+		+	+
2009–2010		+			+	+
2010–2011	+	+			+	
2011–2012	+	+	+			+
2012–2013		+	+	+		+
2013–2014						
2014–2015				+	+	

Source: Own elaboration.

Table 2
Results of decoupling index. Second level decomposition.

Years	Agriculture	Industry	Energy	Transport	Services	Residential
2000–2001	SDE	NDE	SDE	NDE	NDE	NDE
2001–2002	SDE	WDE	SDE	WDE	NDE	NDE
2002–2003	NDE	NDE	NDE	NDE	SDE	NDE
2003–2004	NDE	NDE	NDE	NDE	NDE	NDE
2004–2005	SDE	NDE	NDE	NDE	NDE	NDE
2005–2006	SDE	SDE	NDE	NDE	NDE	NDE
2006–2007	NDE	NDE	SDE	NDE	SDE	WDE
2007–2008	SDE	SDE	NDE	SDE	NDE	NDE
2008–2009	WDE	SDE	NDE	NDE	NDE	NDE
2009–2010	SDE	NDE	NDE	SDE	NDE	NDE
2010–2011	NDE	WDE	SDE	SDE	NDE	SDE
2011–2012	NDE	NDE	NDE	WDE	NDE	NDE
2012–2013	NDE	NDE	WDE	SDE	SDE	SDE
2013–2014	SDE	SDE	NDE	WDE	SDE	SDE
2014–2015	SDE	SDE	NDE	NDE	NDE	WDE
No Decoupling Efforts (NDE), Weak Decoupling Efforts (WDE), Strong Decoupling Efforts (SDE)						

Source: Own elaboration.

intensity indicates that there will be a backfire effect. This is an important finding regarding Spain's energy efficiency policy because this direct effect worsens when the indirect effect embodied in energy activity is added. As mentioned above, during the economic crisis period, energy efficiency levels failed to react in an easy way to fixed consumption levels, but in this second decomposition analysis, we focus directly on effects derived from technological change on energy intensity. These effects go against decoupling between energy consumption and economic growth.

Contrary to what happened in the industry sector, energy intensity did not support Jevon's paradox in the energy sector. Despite this fact, the sector, as a whole, did not show a clear pattern against and with coupling being the population effect as the main barrier for decoupling until changes in the 2012 demographic trend.

Exploring possible direct backfire effects in the transport sector motivate these authors to differentiate between two sub periods. Between 2000 and 2006, the energy intensity effect acted against decoupling, thus causing a direct backfire effect on energy consumption. From the last year of the sub period onwards, mainly positive values higher than one were seen. The energy sector seems to slowly move towards a decoupling status.

The results seem to support Jevon's paradox when focusing on the service sector. Because it is a less technological intensive option, technical improvements in energy efficiency have little chance. Improvements in processes rather than in technology could be a right road to move ahead of the backfire effect. The service sector, as a whole, shows a strong coupling status between energy consumption and economic growth.

Finally, no support of Jevon's paradox appears when analyzing the results for the residential sector, despite of low values for direct energy efficiency effect and an unclear pattern regarding decoupling for the sector.

6. Conclusions

Jevon's paradox or the backfire effect on energy consumption caused by energy efficiency improvements was tested for Spain during the period 2000 to 2015. Here, the backfire effect means that there is a rebound higher than 100%; this implies energy efficiency improvement acting on energy intensity that fails to reduce rather than raise energy consumption. To obtain this, a Logarithmic Mean Divisia Index I (LMDI-I) was used in a novel way to better differentiate between direct and indirect effects in a no-partial equilibrium scenario. A multisectoral approach was conducted to focus on the sectors identified by Spain's plans of action as the most energy intensive ones.

As a whole, our results do not support Jevon's paradox for the sectors analyze. However, they do indicate a possible backfire effect in the industry, transport and service sectors. Major findings follow along the same lines when the activity effect is blocked and when its results are not worsened by those speaking of a backfire effect causes by a direct effect.

Despite the fact that results for the industry sector could be partially explained by fixed levels of energy consumption, it is not easily adjusted during economic crisis years; authorities in Spain might develop strong efforts on this sector together with the transport and service sectors. In the last case, improvements in energy efficiency would derive from innovation in processes rather than technological advances because of low use of the capital factor.

Regarding [15] on energy efficiency, the results do not show that Spain's economy is moving towards a decoupling status between economic growth and energy consumption. Of course, energy efficiency improvements are not the only path to reach it but when the rebound effect is reduced, its inhibitor role on energy consumption increases.

Finally, as the aim of this paper was not to estimate the precise rebound effect caused by the energy efficiency improvements but to test whether such improvements caused a backfire effect offsetting the expected decrease in energy consumption, further research is needed to measure the size of the various types of rebound effects.

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Annexes

Table A.1
Correspondence of productive sectors between the Energy Balance and the GVA

Aggregate Sectors	Energy Balance	Gross Value Added
Agriculture	Agriculture/Forestry	Agriculture, forestry and fishing
	Fishing	
Industry	Mining and Quarrying	Extractive industries
	Food and Tobacco	Food industries, beverage manufacturing and tobacco industry
	Textile and Leather	Textile industry, garment making and the leather and footwear industry
	Wood and Wood Products	Wood and cork industry
		Manufacture of furniture, other manufacturing
	Paper, Pulp and Print	Paper industry
		Graphic arts and reproduction of recorded media
	Chemical and Petrochemical industry	Chemical industry
		Manufacture of pharmaceutical products
	Non-metallic Minerals	Manufacture of rubber and plastic products
	(Glass, pottery & building mat. Industry)	
	Non-ferrous metal industry	Manufacture of other non-metallic mineral products
	Iron & steel industry	Metallurgy, manufacture of iron, steel and ferroalloy products
		Manufacture of metal products, except machinery and equipment
	Machinery	Manufacture of machinery and equipment n.c.o.p.
		Repair and installation of machinery and equipment
	Transport Equipment	Manufacture of motor vehicles, trailers and semi-trailers
		Manufacture of other transport material
	Construction	Construction
	Non-specified (Industry)	Manufacture of computer, electronic and optical products
		Manufacture of electrical material and material
Energy	Consumption of the energy branch.	Supply of electric power, gas, steam and air conditioning
	Includes Oil refineries (Petroleum Refineries)	Coke and oil refining
Transport ([a])	Transport	Transport
Services	Services	Water supply; sanitation activities, waste management and decontamination
		Wholesale and Retail; repair of motor vehicles and motorcycles
		Post and postal activities
		Hostelry
		Information and communications
		Financial and insurance activities
		Real estate activities
		Professional, scientific and technical activities; administrative activities and auxiliary services
		Public administration and defense; compulsory social security; education; health and social services activities
		Artistic, recreational and entertainment activities
		Other services
Residential	Residential	Activities realized in households

([a]) Includes: land and pipeline transport, maritime, air; as well as, storage and activities attached to transport.

Source: Own elaboration.

Table A.2
Type of energy sources used for decomposition at sector level

Sectors	Oil	Gas	Renewables	Electricity	Solid fuels
Agriculture	x	x	x	x	
Industry	x	x	x	x	x
Energy	x	x	x	x	x
Transport	x	x	x	x	
Services	x	x	x	x	
Residential	x	x	x	x	x

Source: Own elaboration.

Table A.3
Additive LMDI-I decomposition by sectors and effects (kilo tons of oil equivalent)

Sectors	Effects	2000−2001	2001−2002	2002−2003	2003−2004	2004−2005	2005−2006	2006−2007	2007−2008	2008−2009	2009−2010	2010−2011	2011−2012	2012−2013	2013−2014	2014−2015
	ΔP	11,953	21,553	49,523	53,497	56,171	48,330	50,188	55,056	31,054	12,246	8863	8247	−5372	−12,995	−3423
	ΔM	−0,247	0002	11,752	0,150	−0,330	−0,201	0012	−0,093	−2828	−0,202	2306	0,267	0013	−0,034	−9414
Agriculture	ΔI	−136,349	−57,110	588,156	477,916	39,492	−468,454	−67,789	−170,183	−240,000	−167,732	59,550	572,091	−216,302	−48,002	−199,650
	ΔS	−136,878	−45,671	−92,935	−168,760	−380,152	46,666	80,358	−114,686	−8798	46,907	112,595	−185,600	393,364	−68,699	−140,858
	ΔA	87,140	44,826	23,136	34,947	54,524	74,910	68,310	−17,755	−114,887	−10,546	−22,237	−82,355	−34,271	47,783	82,088
	Δ Total	−174,381	−36,400	579,631	397,750	−230,295	−298,748	131,079	−247,659	−335,459	−119,327	161,078	312,649	137,432	−81,948	−271,257
	ΔP	126,436	247,214	544,865	510,187	536,244	474,720	483,961	537,759	301,852	120,291	87,795	70,878	−41,640	−98,398	−27,091
	ΔM	0,110	0016	0,414	0148	0,136	−4582	0,028	−0,118	−0,980	0116	−0,470	−0,954	0093	−0,202	−2331
Industry	ΔI	458,003	−273,412	1.512,908	551,005	168,849	−4.854,929	1.039,091	−1.588,609	−1.967,654	2.188,941	847,819	508,417	915,144	−1.119,123	−2.365,192
	ΔS	258,223	−153,613	−278,658	−596,064	−375,413	−445,555	−842,730	−567,458	−1.665,154	−1.440,108	−1.247,552	−754,131	−488,686	130,451	208,021
	ΔA	921,727	514,154	254,555	333,282	520,523	735,810	658,715	−173,419	−1.116,736	−103,596	−220,267	−707,820	−265,656	361,801	649,739
	Δ Total	1.764,498	334,360	2.034,083	798,557	850,339	−4.094,535	1.339,066	−1.791,846	−4.448,672	765,644	−532,674	−883,610	119,256	−725,471	−1.536,854
	ΔP	28,94	53,12	113,88	105,92	112,49	119,43	148,21	162,66	101,46	43,07	30,23	26,58	−16,95	−40,71	−12,29
	ΔM	−0,01	−0,09	0,23	0,00	0,96	66,26	−0,06	−0,37	−0,75	−0,02	−1,40	5,15	−1,66	0,05	9,43
Energy	ΔI	−316,83	−119,76	−162,15	−64,31	−9,36	1.784,81	−529,91	−317,17	127,34	−1.361,48	−772,66	1.830,95	1.626,30	−4,04	−837,64
	ΔS	−105,47	−131,00	249,14	136,98	60,88	−169,60	−15,80	118,61	−63,50	1.312,75	357,93	−232,71	−1.739,47	63,41	1.268,96
	ΔA	210,98	110,48	53,20	69,19	109,20	185,12	201,72	−52,45	−375,35	−37,09	−75,85	−265,47	−108,14	149,70	294,87
	Δ Total	−182,383	−87,250	254,299	247,779	274,171	1.986,028	−195,830	−88,731	−210,805	−42,777	−461,737	1.364,503	−239,921	168,410	723,321
	ΔP	163,31	315,64	689,12	644,45	685,43	661,71	727,45	809,71	486,26	200,28	141,88	112,00	−62,73	−147,52	−44,15
	ΔM	0,60	0,08	0,07	0,01	0,07	1,03	0,47	−0,50	−1,79	−0,20	−0,32	−1,24	−3,81	0,01	1,44
Transport	ΔI	663,50	884,85	2.270,96	1.281,14	2.200,01	705,75	−31,70	−1.096,29	−528,64	−2.432,94	−1.798,77	−2.024,17	317,35	−1.024,42	162,64
	ΔS	−614,48	−1.363,09	−1.473,27	−645,71	−2.243,92	−1.251,44	−444,34	−1.249,17	−777,26	1.686,65	858,07	343,26	−1.414,16	833,32	443,25
	ΔA	1.190,55	656,46	321,95	420,99	665,34	1.025,64	990,12	−261,12	−1.798,97	−172,48	−355,97	−1.118,45	−400,18	542,41	1.058,87
	Δ Total	1.403,482	493,933	1.808,828	1.700,869	1.306,941	1.142,687	1.241,999	−1.797,363	−2.620,402	−718,687	−1.155,107	−2.688,593	−1.563,533	203,807	1.622,050
	ΔP	33,09	64,76	136,22	126,80	140,52	141,33	154,80	177,02	116,04	51,21	38,65	32,71	−18,98	−42,67	−12,63
	ΔM	0,06	0,01	−1,22	0,43	1,81	1,36	−0,02	0,10	0,01	0,05	1,14	−0,02	−0,07	−0,21	5,87
Services	ΔI	91,67	−56,25	−365,79	307,58	279,86	74,01	−582,97	255,23	172,56	270,91	335,25	−11,56	−404,00	−861,55	934,83
	ΔS	2,50	53,38	53,44	86,46	110,86	76,21	109,42	102,55	249,62	113,75	127,79	148,09	113,24	−21,97	−60,07
	ΔA	241,23	134,69	63,64	82,83	136,40	219,06	210,69	−57,09	−429,30	−44,10	−96,97	−326,66	−121,07	156,88	302,86
	Δ Total	368,539	196,594	−113,715	604,113	669,437	511,966	−108,078	477,811	108,938	391,827	405,871	−157,447	−430,878	−769,514	1.170,870
	ΔP	59,24	115,70	256,66	243,59	259,94	250,80	272,21	304,20	195,04	87,56	62,99	50,33	−29,35	−68,45	−19,93
	ΔM	0,32	0,05	0,21	0,05	0,07	0,36	0,00	−0,01	−0,19	0,23	−1,13	−0,01	−0,08	0,00	0,03
Residential	ΔI	−5,42	−210,29	161,80	26,02	−415,01	−295,26	−501,91	−270,25	328,57	505,66	−731,05	1.369,44	144,77	−161,28	−28,02
	ΔS	134,36	186,26	406,61	344,41	363,66	101,42	−95,17	−64,72	626,76	478,26	−465,40	−1.019,25	−571,12	−194,69	−263,01
	ΔA	431,85	240,64	119,91	159,12	252,32	388,74	370,51	−98,10	−721,58	−75,41	−158,05	−502,59	−187,26	251,69	477,98
	Δ Total	620,354	332,354	945,185	773,192	460,973	446,069	45,643	−128,881	428,609	996,298	−1.292,634	−102,083	−643,045	−172,733	167,049

Table A.4
Decomposition effects when blocking activity effect

Sectors	Effects	2000–2001	2001–2002	2002–2003	2003–2004	2004–2005	2005–2006	2006–2007	2007–2008	2008–2009	2009–2010	2010–2011	2011–2012	2012–2013	2013–2014	2014–2015
Agriculture	ΔA	87,140	44,826	23,136	34,947	54,524	74,910	68,310	−17,755	−114,887	−10,546	−22,237	−82,355	−34,271	47,783	82,088
	γ_{POB}	−0,137	−0,481	−2140	−1531	−1030	−0,645	−0,735	−3101	−0,270	−1161	−0,399	−0,100	0157	0,272	0042
	γ_{MIX}	0,003	0000	−0,508	−0,004	0006	0,003	0000	0,005	0025	0,019	−0,104	−0,003	0000	0,001	0115
	γ_{INT}	1565	1274	−25,421	−13,675	−0,724	6254	0,992	9585	2089	15,905	−2678	−6947	6311	1005	2432
	γ_{EST}	1571	1019	4017	4829	6972	−0,623	−1176	6459	0,077	−4448	−5063	2254	−11,478	1438	1716
	γ_{TOTAL}	3001	1812	−24,053	−10,381	5224	4988	−0,919	11,949	0,920	9315	−9244	−5796	−6010	2715	4304
	Meaning	SDE	SDE	NDE	NDE	SDE	SDE	NDE	SDE	WDE	SDE	NDE	NDE	NDE	SDE	SDE
Industry	ΔA	921,727	514,154	254,555	333,282	520,523	735,810	658,715	−173,419	−1.116,736	−103,596	−220,267	−707,820	−265,656	361,801	649,739
	γ_{POB}	−0,137	−0,481	−2140	−1531	−1030	−0,645	−0,735	−3101	−0,270	−1161	−0,399	−0,100	0157	0,272	0042
	γ_{MIX}	0,000	0000	−0,002	0000	0,000	0006	0,000	0001	0,001	−0,001	0002	0,001	0000	0,001	0004
	γ_{INT}	−0,497	0532	−5943	−1653	−0,324	6598	−1577	9161	1762	−21,130	−3849	−0,718	−3445	3093	3640
	γ_{EST}	−0,280	0299	1095	1788	0,721	0606	1279	3272	1491	13,901	5664	1065	1840	−0,361	−0,320
	γ_{TOTAL}	−0,914	0350	−6991	−1396	−0,634	6565	−1033	8332	1984	−9391	0,418	−0,752	−2449	3005	3365
	Meaning	NDE	WDE	NDE	NDE	NDE	SDE	NDE	SDE	SDE	NDE	WDE	NDE	NDE	SDE	SDE
Energy	ΔA	210,98	110,48	53,20	69,19	109,20	185,12	201,72	−52,45	−375,35	−37,09	−75,85	−265,47	−108,14	149,70	294,87
	γ_{POB}	−0,14	−0,48	−2,14	−1,53	−1,03	−0,65	−0,73	−3,10	−0,27	−1,16	−0,40	−0,10	0,16	0,27	0,04
	γ_{MIX}	0,00	0,00	0,00	0,00	−0,01	−0,36	0,00	0,01	0,00	0,00	0,02	−0,02	0,02	0,00	−0,03
	γ_{INT}	1,50	1,08	3,05	0,93	0,09	−9,64	2,63	6,05	−0,34	36,71	10,19	−6,90	−15,04	0,03	2,84
	γ_{EST}	0,50	1,19	−4,68	−1,98	−0,56	0,92	0,08	−2,26	0,17	−35,39	−4,72	0,88	16,09	−0,42	−4,30
	γ_{TOTAL}	1,86	1,79	−3,78	−2,58	−1,51	−9,73	1,97	−0,31	−1,44	−0,85	4,09	−7,14	0,22	−0,12	−1,45
	Meaning	SDE	SDE	NDE	NDE	NDE	NDE	SDE	NDE	NDE	NDE	SDE	NDE	WDE	NDE	NDE
Transport	ΔA	1.190,55	656,46	321,95	420,99	665,34	1.025,64	990,12	−261,12	−1.798,97	−172,48	−355,97	−1.118,45	−400,18	542,41	1.058,87
	γ_{POB}	−0,14	−0,48	−2,14	−1,53	−1,03	−0,65	−0,73	−3,10	−0,27	−1,16	−0,40	−0,10	0,16	0,27	0,04
	γ_{MIX}	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00
	γ_{INT}	−0,56	−1,35	−7,05	−3,04	−3,31	−0,69	0,03	4,20	0,29	14,11	5,05	1,81	−0,79	1,89	−0,15
	γ_{EST}	0,52	2,08	4,58	1,53	3,37	1,22	0,45	4,78	0,43	−9,78	−2,41	−0,31	3,53	−1,54	−0,42
	γ_{TOTAL}	−0,18	0,25	−4,62	−3,04	−0,96	−0,11	−0,25	4,88	−0,54	2,17	1,24	0,40	1,91	0,62	−0,53
	Meaning	NDE	WDE	NDE	NDE	NDE	NDE	NDE	SDE	NDE	SDE	SDE	WDE	SDE	WDE	NDE
Services	ΔA	241,23	134,69	63,64	82,83	136,40	219,06	210,69	−57,09	−429,30	−44,10	−96,97	−326,66	−121,07	156,88	302,86
	γ_{POB}	−0,14	−0,48	−2,14	−1,53	−1,03	−0,65	−0,73	−3,10	−0,27	−1,16	−0,40	−0,10	0,16	0,27	0,04
	γ_{MIX}	0,00	0,00	0,02	−0,01	−0,01	−0,01	0,00	0,00	0,00	0,00	−0,01	0,00	0,00	0,00	−0,02
	γ_{INT}	−0,38	0,42	5,75	−3,71	−2,05	−0,34	2,77	−4,47	−0,40	−6,14	−3,46	0,04	3,34	5,49	−3,09
	γ_{EST}	−0,01	−0,40	−0,84	−1,04	−0,81	−0,35	−0,52	−1,80	−0,58	−2,58	−1,32	−0,45	−0,94	0,14	0,20
	γ_{TOTAL}	−0,53	−0,46	2,79	−6,29	−3,91	−1,34	1,51	−10,37	−2,25	−10,88	−6,19	−1,52	1,56	5,91	−2,87
	Meaning	NDE	NDE	SDE	NDE	NDE	NDE	SDE	NDE	NDE	NDE	NDE	NDE	SDE	SDE	NDE
Residential	ΔA	431,85	240,64	119,91	159,12	252,32	388,74	370,51	−98,10	−721,58	−75,41	−158,05	−502,59	−187,26	251,69	477,98
	γ_{POB}	−0,14	−0,48	−2,14	−1,53	−1,03	−0,65	−0,73	−3,10	−0,27	−1,16	−0,40	−0,10	0,16	0,27	0,04
	γ_{MIX}	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00	0,00	0,00
	γ_{INT}	0,01	0,87	−1,35	−0,16	1,64	0,76	1,35	2,75	−0,46	−6,71	4,63	−2,72	−0,77	0,64	0,06
	γ_{EST}	−0,31	−0,77	−3,39	−2,16	−1,44	−0,26	0,26	0,66	−0,87	−6,34	2,94	2,03	3,05	0,77	0,55
	γ_{TOTAL}	−0,44	−0,38	−6,88	−3,86	−0,83	−0,15	0,88	−0,69	−2,59	−15,21	6,18	−1,80	1,43	1,69	0,65
	Meaning	NDE	NDE	NDE	NDE	NDE	NDE	WDE	NDE	NDE	NDE	SDE	NDE	SDE	SDE	WDE

Appendix A. Supplementary data

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