“Accepted for publication in Energy, June 2021 - authors' final version”

Can a combination of efficiency initiatives give us “good” rebound effects?

Cristina Sarasa[a*] and Karen Turner[b]

[a]Department of Economic Analysis. University of Zaragoza, Zaragoza (Spain) and Agrifood Institute of Aragon (IA2), Zaragoza (Spain), corresponding author

[b]Centre for Energy Policy, School of Government and Public Policy, University of Strathclyde, Glasgow (United Kingdom)

Abstract:

The increasing depletion of natural resources, combined with a wider set of pressures on the environment, has, in recent years, highlighted the need for a more efficient use of energy and a development process that involves alternative energy sources. Energy efficiency has received much attention as a solution, implying both monetary and emissions savings. However, the latter may be partially offset by the income and demand effects of the former, both in more efficient sectors and in spreading to the wider economy. This is the problem of rebound effects. Taking Spain as a case study, and introducing an energy-related CGE model that develops the inclusion of renewables, this paper evaluates a combination of efficiency initiatives to deliver both reduced energy use by households and a more sustainable supply of energy. Our findings suggest that a package aimed at improving efficiency in household electricity and petroleum use, combined with a more competitive supply of energy from renewable sources, may be the only way to get reductions in all energy use, and thus benefit the economy. Specifically, we consider how this package may lead to positive economic impacts and associated rebound effects, where the latter are focused on a greener energy supply.

Keywords: Rebound effects; renewable energy; CGE model; efficiency improvements.
JEL codes: C67, C68, Q2, Q4.

Can a combination of efficiency initiatives give us “good” rebound effects?

1. Introduction

The increasing depletion of natural resources, combined with the associated environmental and global climate damage, has highlighted the need for a more efficient use of energy and a development process that involves alternative energy sources. There is a clear recognition that efficiency must increase across all links of the energy chain, from generation to final consumption, to improve economic and environmental sustainability (see IPCC, 2014; European Commission, 2017). Recent studies warn against countries planning to produce more than double the amount of fossil fuels by 2030 than would be consistent with a 1.5°C temperature limit (see SEI, 2019). Thus, more responsible and efficient use of non-renewable energy and increased reliance on renewable sources is more necessary than ever. Particular attention has focused on the use of energy, especially where this may enable citizens to lower their energy bills, reduce their reliance on oil and gas, and thereby reduce their impact on the environment. Renewable energy offers a sustainable alternative and is considered to be ‘the energy of the future’ (European Commission, 2017). Clean, low-carbon, energy comes mainly from a range of sources including wind, solar, and water, but there are challenges in terms of whether - and how - energy from renewable sources can provide a competitive and affordable alternative to non-renewable supplies.

Much attention in the literature on energy efficiency has focused on aggregate ‘energy’ use in the household and industrial sectors, with little attention paid to the supply of that energy and scant specific focus on the nature of, and interactions between, monetary and energy savings. The literature on the issue of ‘rebound effects’ has examined how energy savings from increased efficiency generate monetary savings that trigger (direct and indirect) demand responses that serve to erode the initial gains. This literature tends to build on the work of Jevons (1865), which was, of course, set in the context of the industrial revolution, where energy was largely derived from fossil fuel sources, and has developed through a large body of more recent research, including commonly cited works such as Saunders (1992), Sorrell et al. (2009) and Van den Bergh (2011). However, while in recent years a growing literature has tried to estimate rebound effects for different theoretical and applied cases, there is an ongoing lack of consensus on how to estimate them empirically, combined with a lack of attention to energy supply responses (see Turner, 2013) and, more generally, to the nature of that supply. One issue that we focus on here is whether a rebound effect is, in and of itself, a 'bad' thing, or should the concern really lie in the type of energy we 'rebound' into, particularly when driven by positive economic responses to increased efficiency?

In this context, our main objective is to consider whether a combination of initiatives aimed at (1) increasing efficiency in household use of different types of energy *and* (2) improving the efficiency (and thereby relative competitiveness) of electricity produced from renewable sources, may deliver more favourable economic and 'rebound' outcomes. For the case of Spain, we use an energy-related Computable General Equilibrium (CGE) modelling framework that develops the inclusion of renewable energies in production and consumption. Multi-sector CGE techniques have been the standard approach in considering rebounds and their drivers at the economy-wide level (Sorrell, 2007), and have been particularly useful in exploring the rebound effects of efficiency improvements in energy use. We build on energy-focussed CGE works that consider both economy-wide rebound effects and the economic expansion processes that drive them. Examples of such studies are as follows. Lecca et al. (2014) investigate the economic impact of a 5% improvement in the UK household energy efficiency (i.e. technical change that allows a given level of household consumption using 5% less energy), focusing on total energy rebound effects. Figus et al.

(2017) extend this work in the context of considering the case for public support of energy efficiency actions in different household income groups within the UK. Duarte et al. (2016), evaluate the economic and environmental impacts of improvements in environmental awareness, changes induced by regulation in energy efficiency and carbon taxes in Spain. Also focussing on a Spanish case, Duarte et al. (2018) studied the economic impact of certain consumer-oriented measures, focused on more efficient technologies of electricity consumption and the use of transport services, with a dynamic CGE model. Also using a dynamic CGE model, Lekavicius et al. (2019) studied the full impact of increased domestic electricity generation in the Lithuanian economy, while Figus et al. (2020) explored the effects of price 'stickiness' in energy supply on the evolution of rebound effects. Koesler et al. (2016) take a different production-side focus, focussing on energy use in an industrial setting, and incorporate international spill-over effects from trade into analysis of rebound effects associated with industrial energy efficiency in Germany. More recently, Khoshkalam Khosroshahi and Sayadi (2020) explored the economy-wide rebound effects of 5%, 7%, and 10% energy efficiency improvement shocks at sector and wider economy levels in Iran. Du et al. (2020) analyzed the rebound effect from an improvement of 10% in energy efficiency on the transportation sector in China. Finally, Brockway et al. (2021) present an interesting review of different methodologies and approaches, to study the economy-wide rebound effects from improved energy efficiency.

Here, we contribute to and extend this literature by introducing a higher level of detail for the energy and transport sectors, in both production and consumption, than is commonly the case in CGE studies. In particular, we focus on the specification of renewable electricity supply in the input-output data for Spain, which constitutes the core database for the calibration of the CGE model. Our model thereby allows for extensive substitution possibilities within energy sources and sectors, and in transport services, with the inclusion of private car and public uses. This model presents a clear contribution to the study of rebound effects distinguishing between renewable and non-renewable energies.

Spain presents great potential for renewables, as it is one of the 20 leading countries in renewable energy production and one of the 5 leading countries in such production per capita (REN21, 2017). However, Spain has a high level of external energy dependence (about 80%), largely relying on imports to meet its energy needs (Eurostat, 2017). The European Union (EU) has mandated the promotion of renewable energy (The Renewable Energy Directive (2009/28/EC) (RED, 2009), and the post-2020 EU Renewable Energy Directive (RED II, 2018). Recently, National Energy and Climate Plans (NECPs, 2018) have been established by EU Member States for the period 2021-2030. It is in this context that Spain's energy policy continues to develop, with national action plans placing particular emphasis on improving efficiency in energy use and developing domestic renewable energy sources.

This is a convincing route to shedding greater light on the impacts of alternative efficiency initiatives through a range of scenarios. First, we consider increased energy efficiency in household consumption, focusing primarily on electricity use and later introducing efficiency in fuel use in private transport (which is impacted by the income effects of increased efficiency in electricity use). Second, we focus on increased capital and labour productivity in the production of electricity from renewable sources. We then combine the two in a simultaneous scenario analysis to assess the results of alternative combinations.

The rest of the paper is organized as follows. Section 2 describes the Spanish context for the applied modelling. Section 3 outlines our methodology and data. Section 4 presents the impacts of alternative efficiency scenarios, with a focus on electricity supply and use. Section 5 then analyses a problem of rebound in petroleum use that emerges from the preceding analysis, and Section 6 presents our concluding remarks.

2. Energy efficiency and renewables: The Spanish context

As noted above, Spain plans to establish targets to improve energy efficiency, reduce emissions, and increase the share of energy from renewable sources. Specifically, the Spanish National Energy and Climate Plans establishes a target of 32.5% energy efficiency, 40% emissions reduction, and a 32% share of energy from renewable sources in gross final consumption of energy, all by the year 2030 (NECPs, 2018). Moreover, as is plain from the literature (see Alsaleh et al., 2017, and Abdulwakil et al., 2020), technical efficiency in all regions of the EU28 must be reviewed as it is the most important concept in leading the EU region to achieve its environmental targets.

The Spanish measures focus on both the effects of technology and efficiency improvements implemented in production and consumption. On the consumer side, focusing on private households, the adoption of new appliances with energy efficiency levels is addressed through awareness campaigns that emphasise efficiency as one of the primary measures in reducing emissions, in line with the EU SDS (European Union Sustainable Development Strategy, 2009). A key point to note is that, in existing Spanish data (IDAE, 2010), household appliances are recorded as being powered only by non-renewable electricity. This means that the focus on more efficient appliances may, in fact, reduce demand for electricity generated from non-renewable sources. Moreover, the measure is intended to be implemented through the routine replacement of appliances, where new appliances are manufactured to be more efficient, with the implication that no additional costs are involved. On the production side, the promotion of energy from renewable sources requires technological progress to permit more efficient and competitive production. In Spain, as in many other countries, renewable energy sources have been subsidised for around 15 years, a policy intervention that has permitted construction and development of a large number of renewable energy installations. Further subsidies have been promoted since the onset of the COVID-19 crisis, earmarked to renewable energy projects that generate power from solar, wind, biomass, and renewable gases like hydrogen, with the aim of providing sectors such as agriculture, industry, and services with more renewable energy. Thus, renewable generators must pursue options to achieve and maintain competitiveness by reducing production costs through increased efficiency. This is the position that we take in the CGE simulation work in this paper.

In general terms, we model the interacting impacts of energy supply and demand policies on the Spanish economy, and the nature of rebound effects. More specifically, we focus on how more competitive renewable options may induce households to reduce their dependence on non-renewable electricity as they increase their efficiency in electricity use.

3. A Spanish CGE model for considering renewable energy and energy efficiency issues

We develop a multi-sector, static Computable General Equilibrium (CGE) model of the Spanish economy, calibrated using the Spanish Input-Output Framework (symmetric IOFA-10) available from NSI (2010)[1]. Our model builds on previous energy-related CGE models for Spain (Duarte et al. 2014 and 2018), here developing focus on renewable energies both in production and consumption functions. The production side of the economy is represented by 39 production sectors. The energy sector is disaggregated at a detailed sub-sector level, including four energy accounts: coal, petroleum, gas, and non-renewable electricity, and five branches of renewable energy: wind, hydroelectric, solar, biomass, and biofuels. Here, we present an overview of the key model features.

---

[1] This year experienced average economic growth and includes the main expansion of renewables addressed in Spain, as a relaxation in this expansion was experienced in the following years.

3.1. Producers

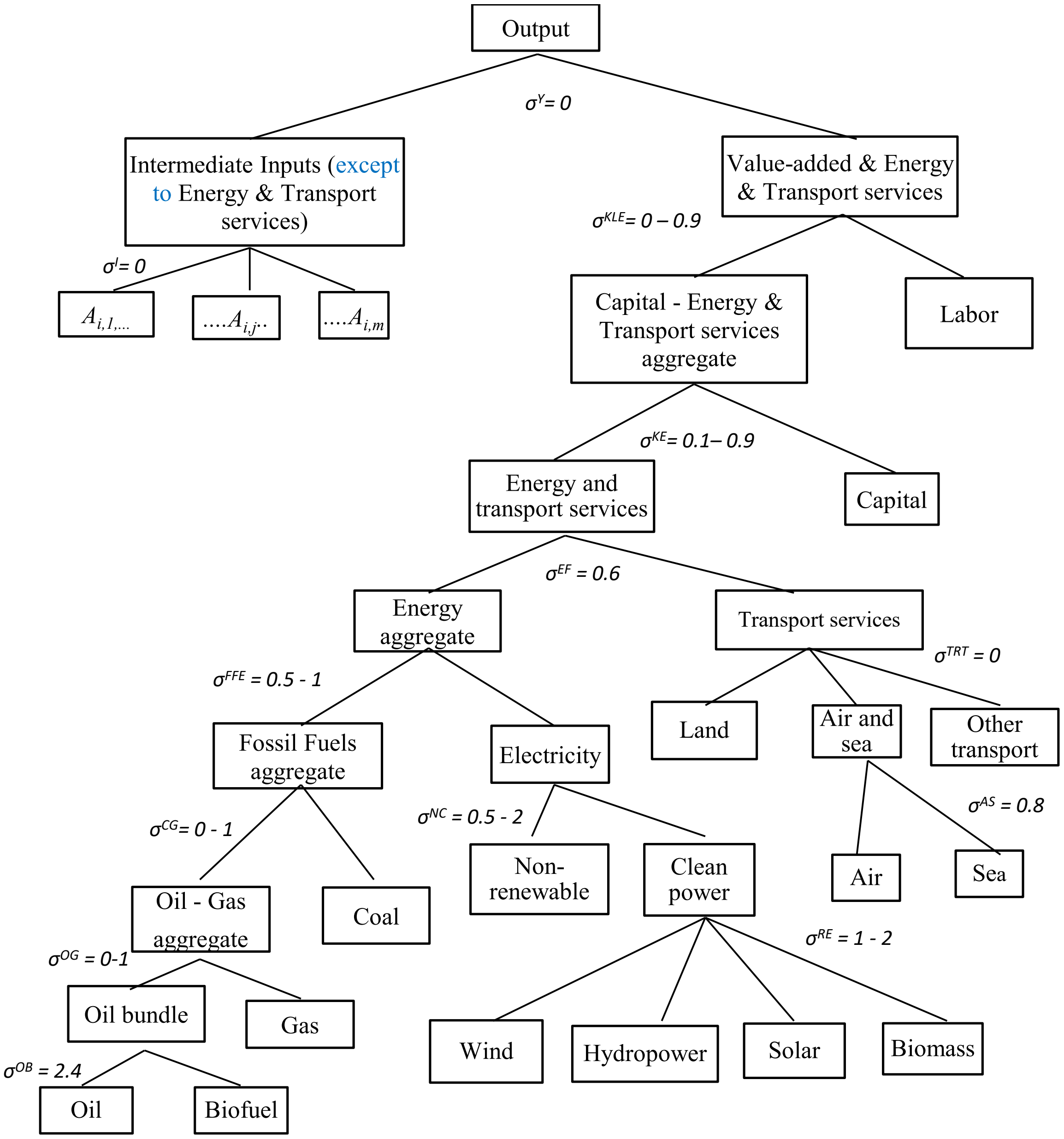
Each of i=1,…,N = 39 producers or industry sectors minimize costs through a multi-level constant elasticity of substitution (CES) production function, as illustrated in Figure 1, following a production structure similar to the GTAP-E model (Burniaux and Truong, 2002) for the energy aggregate, and similar to Liu and Bohlin (2012) for the transport services substitution. Here a partial intermediate input composite, coupling 'Energy and transport services'[2], together with capital, before the resulting composite combines with labour. The 'value added-energy aggregate-transport services' composite then combines with all other intermediate inputs to give total output, assuming a Leontief (fixed technical coefficients) function at this level.

Demand for energy is a CES composite of electricity and a fossil fuels aggregate, which is itself a CES composite of coal and oil-gas that represents an additional bundle for substitution between oil and biofuel. We introduce a new development for Spain in the form of the substitution between non-renewable electricity and a composite of possibilities representing 'clean power', which is a CES composite of wind, hydroelectric, solar, and biomass renewable generation options.

---

[2] Travelling by air and sea are distinguished within an additional nest as it is more difficult to substitute between those and other forms of transport because they are not used for short distance transport activity. Within this nest, in the absence of information on substitutability in response to changing relative prices, Leontief technology is assumed.

Figure 1. Nested structure of production



Source: Own elaboration

It should be noted that, in the current work, the electricity nest acts as an imperfect proxy for a more sophisticated treatment of electricity supply. In the present treatment, each of the renewable and non-renewable options is from a production sector *i*, with each sharing the nested production structure in Figure 1 and selling its outputs to other production sectors and to different types of final consumption (see below). However, in practice, electricity generators do not sell their output directly to users. Rather, output is sold to a transmission/network and distribution sector(s), which then sells what becomes the homogenous good of electricity to users. In the current treatment, we are effectively assuming that the intermediate transaction within the overall electricity 'sector' is based on a relative price of output from each generator, and we capture this within the decision of the user. However, a future research priority must be to more effectively capture the electricity supply process in CGE models, where other issues relating to, for example, industrial structure, pricing, and capacity decisions at the margin and over time, need to be considered, in line with new work in this line such as Sue Wing (2006, 2008) and the work of Cai and Aora (2015) for the U.S.[3]

3.2. Factor markets

We assume that both labour and capital are mobile across sectors, but with their total supply fixed at the national level. Capital is fully employed, implying a Marshallian long-run interpretation of the simulation results, where all factor use is fully adjusted to the ruling factor and commodity prices, in line with Koesler et al. (2016). This assumption means that return to capital is not specified at the sectoral level, so that the type of differential impacts in capital rental rates in the energy supply sectors, and the 'disinvestment' in energy supply observed in dynamic treatments, such as those of Allan et al. (2007) and Turner (2009), will not occur here.

We also assume that labour is mobile across sectors, with the total supply fixed. However, we introduce a pool of unemployed labour to permit the assumption of some excess capacity in the labour market, and relate this to an assumption of imperfect competition. This is

---

[3] Moreover, it may be that improved treatments of electricity and other energy supply industries may involve interactions with energy system models.

introduced through a wage curve specification, where wages are negatively related to the unemployment rate.

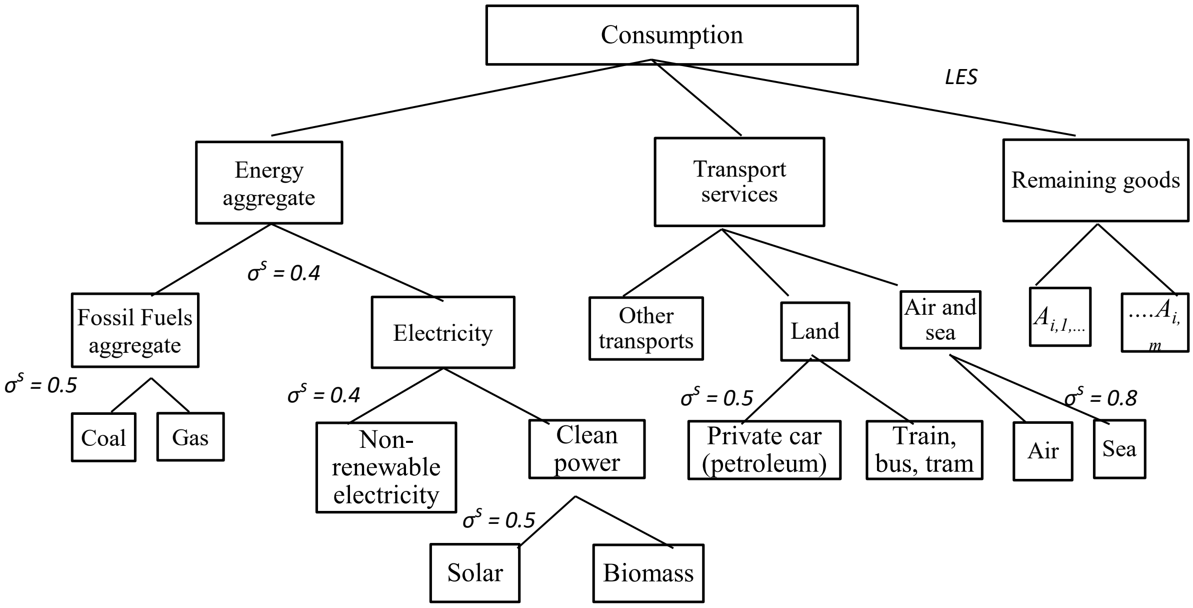
3.3. Consumers

There are four components of final demand: private (household) consumption, government final demand, capital formation, and exports to the rest of the European Union (REU) and to the rest of the world (ROW). In the case of household consumption, consumer preferences are defined by the four-stage nested CES utility function shown in Figure 2. The total demand for energy is a CES composite of electricity and fossil fuel aggregates. The electricity bundle includes non-renewable and clean power (solar and biomass), which is new for Spain and makes the same assumption as described above for users on the production side of the economy, where this nest effectively proxies for an intermediate stage between generator and end consumer. It is here that we focus attention in terms of household substitution, in favour of renewable sources in running appliances if the competitiveness of this option improves, relative to non-renewables (which dominate household consumption for appliances). Note that wind and hydropower are not included because electricity generated from these sources is not transmitted to domestic users in Spain. In the case of transport services, consumers choose the means of transport, following a Leontief function, between (a) land, (b) air and sea and (c) other transport, on the assumption that this decision depends on distance travelled rather than relative prices. Within land transport, we assume that consumers choose between public transport and private vehicles, where the latter is represented by petroleum use.[4]

---

[4] In future research, we aim to consider how the private transport option actually involves combined use of petroleum and investment in vehicles as durable goods.

Figure 2. Household consumption nesting structure



Source: Own elaboration.

3.4. Calibration data

The model is calibrated for the Spanish economy of 2010, and we follow the breakdown of renewable energies updates in the economic structure developed by Cámara et al. (2013), using energy data obtained from the Secretary of State (Energy), provided by the Ministry of Industry, Tourism and Trade of the Government of Spain (MINETUR, 2010), and the Annual Report of Energy Consumption, by IDAE (2010).

The elasticity parameters of different production and consumption nests differ by sector and have been selected on the basis of a review of the relevant literature and studies in this field, and are presented in Table SI1 in the Supplementary Information (SI). Additionally, Table SI3 in the SI shows a quantification of the rebound effect in the Spanish economy based on the formulation provided by Lecca et al. (2014).

4. Impacts of alternative efficiency scenarios

4.1. A first block of simulation strategies

We simulate two types of efficiency scenario: (1) increased energy efficiency in household consumption, focusing mainly on efficiency in electricity use, but later introducing efficiency in other (personal transport) fuel use; (2) the production of more competitive electricity from renewable sources by means of improvements in capital and labour productivity in these energy supply sectors. The efficiency improvements are simulated as technological improvements in the use of a specific input to consumption or production.

That is, in the household consumption case, an efficiency improvement in the use of electricity means the user obtains the same utility level using less electricity input. This acts to lower the effective price of electricity, or the cost of the service obtained from its use. The reduced cost of electricity use in consumption (which will be amplified if reduced demand also affects the market price for electricity), frees up income to spend on other goods and services, thereby triggering a demand-led expansion. We assume that the improvement in efficiency in electricity use is embedded in the routine replacement of obsolete or low-efficiency domestic devices, with appliances labelled Class A or higher, so that there is no additional cost to realising the efficiency gain, certainly not over the long-run context of our simulations.

In the case of more efficient production of renewable electricity, we assume that this is achieved through combined labour- and capital-augmenting technological progress. This technological change is based on the learning process in the use of renewable energies over several years. Again, in the long-run setting of our simulation, it is appropriate to assume that any costs of implementation (occurring in the shorter run) do not impact results. The main focus of our analysis is to determine the resulting impact on the competitiveness of renewables relative to other options, particularly in the household consumption decision.

In summary, we consider three central scenarios. In the first of these, we apply a 10% efficiency improvement in household non-renewable electricity use. This scenario is based on both the use of electrical appliances and lighting in Spanish households via consumption of non-renewable electricity in 2010 (IDAE, 2010). In the second scenario, we simulate a 10% improvement in efficiency in the use of capital and labour in the production of each renewable energy sector. These include the four renewable electricity sectors - wind, solar, hydropower, and biomass - and also biofuels. This means that production in these sectors becomes more competitive, so that we have a cost-push expansion in the economy, but one where renewable electricity generation expands through increased demand overall and through substitution away from competing, non-renewable electricity generation. The third scenario combines both of these simulations, to allow us to consider how the presence of more competitive, renewable electricity production may impact the nature of the expansion and the rebound effects of increased efficiency in household electricity use.

The results from these scenarios are presented in Tables 1 and 2. Detailed price results by sector are shown in the Supplementary Information. Figure 3 represents the changes in total energy use in the economy.

4.2. Scenario 1: Increased efficiency in household non-renewable electricity use

The improvement in household electricity use provokes a 7.748% saving in household non-renewable electricity consumption, involving decreases in all energy demands (Table 1). These drops in energy demand are due to the energy intensity of electricity production itself, with declines in total energy (Figure 3). Energy production experiences reductions because of the contraction in demand.

Small increases in energy prices are observed because of the long-run view that involves adjustments in competitiveness from these production declines. The incentive for non-energy goods entails falls and/or smaller increases in the price of non-energy goods, reflecting the improvements in price competitiveness for non-energy goods (see changes in prices in Table SI2 of the SI). Interestingly, a drop is not registered in petroleum consumption, which increases by 0.282%. Note that this is associated with transport fuel for the use of private vehicles (see Figure 2 above). Additionally, this improvement sets aside the promotion of renewable energies, which reduces production, industry use, and consumption.

Regarding the macroeconomic results (Table 2), the improvement in household non-renewable electricity use leads to an expansion in the economy as a whole: total domestic output, total private consumption, and GDP, by 0.057%, 0.281% and 0.152% respectively. This is in line with the promotion of labour demand via a decline of 0.651% in the unemployment rate and an increase in real wages of 0.046%. Trade is also encouraged with increases in exports due to falls in non-energy prices. These positive results are induced by the switch in demand towards non-energy goods and services that lead to increased supply of those goods after the electricity saving, and the corresponding income and substitution effects. The reduction in the consumer price index (CPI) is due to the falls in non-energy prices that do not outweigh increases in energy prices. These results are in line with the prior literature (see Lecca et al. 2014), noting again that our model reflects a Marshallian long-run interpretation of the simulations.

Table 1. Percentage changes in energy supply sectors in sectoral price, output, industry, and consumption use variables in Scenarios 1, 2 and 3

	Scenario 1				Scenario 2				Scenario 3			
	Production	Prices	Industry use	Consumption	Production	Prices	Industry use	Consumption	Production	Prices	Industry use	Consumption
Coal	-0.491	0.004	-0.453	-3.646	-0.045	-0.001	-0.061	-0.093	-0.535	0.003	-0.512	-3.736
Petroleum	-0.208	0.006	-0.480	0.282	-0.040	-0.001	-0.094	0.038	-0.247	0.004	-0.572	0.320
Electricity non-renewable	-2.112	0.053	-0.581	-7.748	0.000	-0.282	-0.024	0.065	-2.110	-0.229	-0.601	-7.689
Gas	-1.651	0.076	-1.238	-3.681	-0.197	0.014	-0.217	-0.100	-1.843	0.090	-1.449	-3.778
Wind	-2.079	0.037	-2.079		4.235	-2.643	4.235		2.076	-2.610	2.076	
Hydropower	-2.106	0.051	-2.106		4.798	-2.905	4.798		2.598	-2.859	2.598	
Solar	-2.007	0.015	-1.986	-2.305	4.111	-2.677	4.315	1.292	2.025	-2.664	2.248	-1.042
Biomass	-1.698	0.005	-1.168	-2.300	-0.230	-0.179	-0.462	0.017	-1.923	-0.174	-1.619	-2.284
Biofuels	0.122	0.001	0.122		0.118	-0.075	0.112		0.239	-0.074	0.233	

Figure 3. Percentage change in total energy use (industry and households) in Scenarios 1, 2 and 3

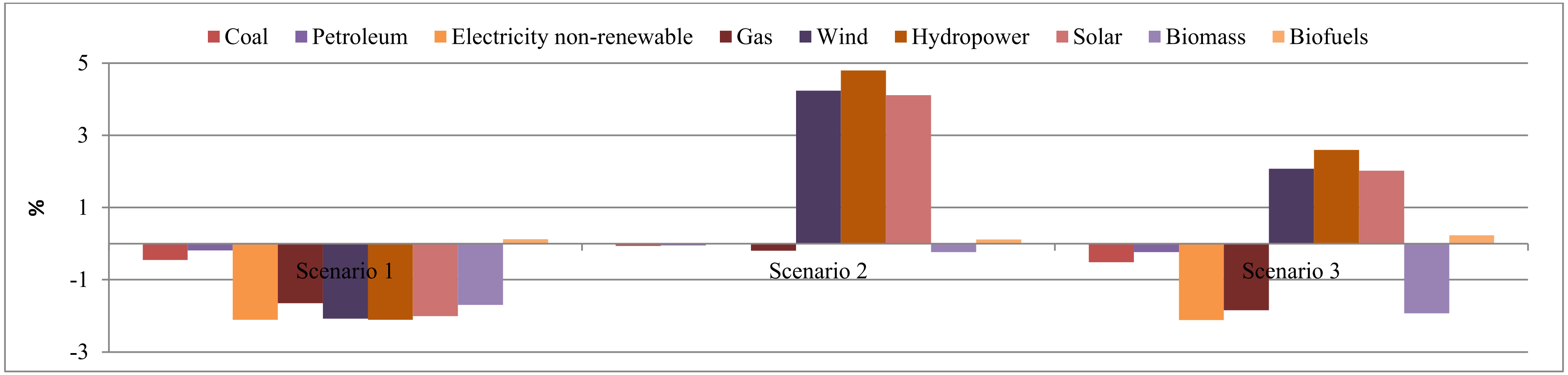


Table 2. Percentage change in key macroeconomic indicators in Scenarios 1, 2 and 3

	10% increase in efficiency in electricity consumption (non-renewable)	10% increase in efficiency in production factors of renewable energies	Scenarios 1 and 2
	Scenario 1	**Scenario 2**	**Scenario 3**
GDP (expenditure approach)	0.152	0.027	0.178
Total domestic output	0.057	0.045	0.101
Total exports	0.140	0.045	0.184
Total imports	0.084	0.034	0.117
Total private consumption	0.281	0.036	0.316
Unemployment	-0.651	-0.121	-0.769
Nominal wages	-0.112	0.016	-0.096
Real wages	0.046	0.008	0.054
CPI	-0.158	0.008	-0.150
Capital rental rate	0.165	0.030	0.195

4.3. Scenario 2: More competitive renewable electricity production

Scenario 2 reports the impacts of more competitive renewable energies through improvements in factor productivity. The objective of this simulation is to induce a reallocation of energy use to encourage the use of renewables. As noted, this technological improvement involves using fewer factors to reach the same level of output. This means more competitive prices with large declines in all renewable prices (Table 1), while the majority of prices in other sectors rise, in line with increases in nominal wages and the CPI (Table SI2 of the SI). As shown in Table 2, this saving resource has a positive result in the wider economy, with improvements in key macroeconomic indicators and a significant increase in the penetration of renewables, reported in increases in output of renewable supply sectors (Table 1) and in the total use of energy (Figure 3). However, these albeit positive results in the wider economy are less favourable than those observed where efficiency improvements occur in household non-renewable electricity use. Greater gains in factor productivity would be required to trigger more positive outcomes (Table 2).

This scenario achieves the objective of increasing the penetration of renewable energies in the economy. Outputs of wind, hydropower, and solar energies increase by around 4%, in concert with renewable energy use in industry, and household consumption of renewables is also enhanced. Results in biomass and biofuels production reveal a lack of predominance of capital-intensive factors in these sectors, relative to other renewables[5]. Within the latter, wind and hydropower register a large increase because they have a larger share in the baseline and their economic structure is more advanced in comparison with the others.

By contrast, consumption of non-renewable electricity increases, along with petroleum use, demonstrating that encouraging renewable energies in isolation, i.e without paying attention to other energy sources, leads to a general boost in the use of non-renewables.

4.4. Scenario 3: Combining efficiency in household non-renewable electricity and more competitive renewable energies

A combination of an increase in efficiency of household electricity use with more competitive renewable energies is presented in Scenario 3. This combination strengthens the positive results in the economy as a whole, dominated by the influence of Scenario 1. The targeted increase in renewable energy use in the overall economy is reached, while the use of non-renewables is visibly reduced, as shown in Figure 3. The combination of both strategies, reflected across Scenarios 1 and 2, provides a boost for renewables, particularly wind, hydropower, and solar, taking advantage of synergies derived from both scenarios, with reductions in the production and consumption of non-renewable energies, such as coal and gas. Thus, while macroeconomic results from Scenarios 1 and 3 are quite similar, there is a reallocation of energy use towards renewables in Scenario 3.

In contrast, the increase in petroleum consumption persists in this scenario. This suggests that additional support focused on the use of petroleum by households is targeted.

---

[5] A separate analysis of labour and capital highlights the high labour intensity required by solar energy.

A detailed analysis of the rebound effects of these scenarios can be observed in Table SI3 of the SI. Rebound occurs when the proportionate reduction in energy use is lower than the increase in efficiency. The 7.748% fall in household electricity use is the result of the 10% efficiency in household electricity use in Scenario 1; there is a rebound of 22.52% in household electricity use, which is slightly larger in Scenario 3, with a greater reduction in household electricity use resulting from the additional impact of the improvement in factor productivity. Therefore, despite very similar economy-wide rebounds in all energy use by households in Scenarios 1 and 3, the use of energy is quite different, as we observed in Figure 3. The total fall in household energy use is 3.69% in Scenario 1, and 3.65% in Scenario 3. The interesting point is the reallocation in the use of energy between both scenarios. Similarly, the proportional impact on electricity use in the overall economy is greatly reduced. Note that the rebound generated in electricity use in the economy as a whole is now smaller in Scenario 3, indicating that more competitive renewables stimulate a larger reduction in the use of non-renewables.

Another interesting result is the presence of negative rebound results. Our quantification of rebound effects includes all of the indirect effects, negative and positive, see Table SI3 of the SI. The proportionate falls in total energy use are greater than the proportionate increase in efficiency. That is, the 1.21% drop in total energy use is larger than the proportional 0.80% efficiency associated with all energy use in Scenario 1, and similarly in Scenario 3. However, it is very important in Scenario 3, which, despite increasing renewable energy use (see Figure 3), shows a reduction in total energy use (both renewable and non-renewable). This is due to the declines in non-renewable energy production observed in Table 1, implying a reduced use of energy, which constrains the rebound effects. This again confirms the importance of the components of the energy mix, and its potential reallocations.

5. The problem of rebound in other energy uses (the problem of petroleum)

5.1. Searching for efficiency initiatives

Efficiency improvements in household electricity use, and more competitive renewables, achieve the objective of non-renewable energy savings while stimulating renewable energy use. However, the greater disposable income for consumers, because of the reduction of costs triggered by energy savings, also stimulates consumption of petroleum by private vehicle use (rebound). This indicates a trade-off between economic stimulus and energy use, and thus a deficiency in accomplishing the goal of reducing overall use via non-renewables. In view of this, a 10% improvement in household fuel use is addressed in a fourth Scenario, in which citizens are considered to drive more efficiently in more efficient vehicles that require less fuel.

Then, the increases in demand efficiency analysed in Scenarios 1 and 4 are tackled in Scenario 5 to evaluate the impacts of consumer-oriented policies. Scenario 6 presents a package of initiatives that incorporates all energy efficiencies, together with more competitive renewables. This last scenario implies a potential solution to the trade-off presented by reducing all energy uses and shows the rebound effects of all improvements together. Tables 4 and 5 present these results, and Figure 4 shows the impacts on total energy use of these simulations.

Table 3. Description of simulation strategies

Scenario 1: Efficiency in household electricity use (non-renewable)	**Scenario 4**: Efficiency in household fuel use (non-renewable)
Scenario 2: Efficiency in production factors of renewable energies	**Scenario 5**: Efficiency in household electricity and fuel use
Scenario 3: Efficiency in household electricity use + Efficiency in production factors of renewable energies	**Scenario 6**: Efficiency in household electricity and fuel use + Efficiency in production factors of renewable energies

5.2. Scenario 4: Efficiency in household fuel use

The improvement in household petroleum use drives an initial saving that allows for increased use of non-petroleum goods, which boosts positive results in the economy in terms of GDP, total private consumption, and total output. This again has a corresponding stimulus in the labour market, with declines in unemployment and increases in real wages. By contrast, trade impacts are negative, due to both exports and imports of petroleum being reduced significantly, triggered by the contraction in petroleum demand.

This scenario itself attains reductions in petroleum use that drive significant declines in petroleum production, while boosting the rest of the energy sources (Table 5). Additionally, production of land transport services are also reduced, along with coal output.

5.3. Scenarios 5 and 6: Packages of efficiency initiatives

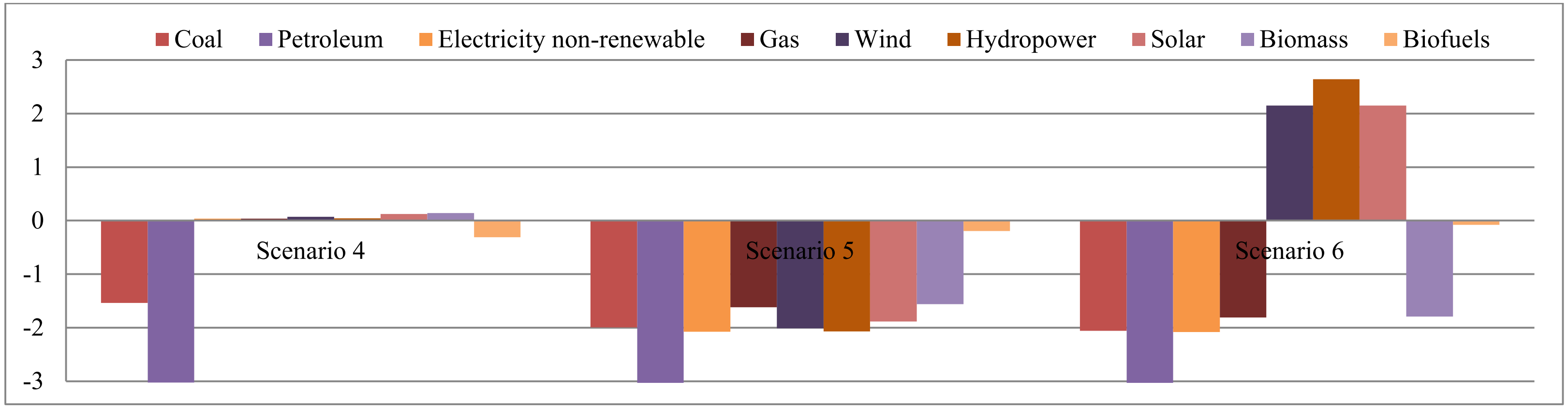
A package of improvements in household electricity and petroleum use achieves reductions in all energy uses, with the related positive results in the economy as a whole being due to the stimulus in non-electricity and petroleum goods. However, renewable energy uses are also reduced, which fails to strike a sustainable path to boosting renewable sources. This is observed in declines in production of renewable energies in Table 4 and in the total energy use in Figure 4.

With a package of efficiency improvements in household energy use and more competitive renewable energies (Scenario 6), we observe a significant boost to the economy as a whole, with increases in GDP, in total private consumption, and in total output, of 0.308%, 0.521% and 0.118%, respectively. The results also indicate greater positive results for the labour market. (See Table 5.)

Table 4. Percentage changes in energy supply sectors in sectoral price, output, and consumption variables in Scenarios 4, 5 and 6

	Scenario 4				**Scenario 5**				**Scenario 6**			
	Production	**Prices**	**Industry use**	**Consumption**	**Production**	**Prices**	**Industry use**	**Consumption**	**Production**	**Prices**	**Industry use**	**Consumption**
Coal	-1.550	0.005	-1.536	0.231	-2.045	0.010	-1.994	-3.424	-2.091	0.009	-2.055	-3.514
Petroleum	-3.049	0.007	-0.693	-6.819	-3.266	0.013	-1.177	-6.556	-3.306	0.011	-1.269	-6.521
Electricity	0.037	0.061	-0.007	0.205	-2.080	0.114	-0.590	-7.559	-2.078	-0.169	-0.610	-7.499
Gas	0.036	0.084	0.006	0.191	-1.618	0.160	-1.234	-3.497	-1.810	0.174	-1.446	-3.594
Wind	0.073	0.043	0.073		-2.011	0.080	-2.011		2.151	-2.571	2.151	
Hydropower	0.042	0.059	0.042		-2.069	0.110	-2.069		2.642	-2.805	2.642	
Solar	0.127	0.019	0.120	0.221	-1.886	0.034	-1.872	-2.090	2.152	-2.647	2.368	-0.823
Biomass	0.144	0.008	0.072	0.226	-1.559	0.012	-1.099	-2.079	-1.784	-0.167	-1.552	-2.063
Biofuels	-0.312	0.003	-0.312		-0.192	0.004	-0.191		-0.075	-0.071	-0.080	

Figure 4. Percentage change in total energy use (industry and households) in Scenarios 4, 5 and 6



One point of interest is the reductions in the consumption of all energy uses, combined with increases in the production of renewables, and in the use of renewables by industries and households. Figure 4 shows that this scenario reaches the level of penetration targeted for renewables in total energy use, combined with reductions in non-renewables. Note that both biomass and biofuels do not increase their production, since they are less capital-intensive and other stimuli are required to boost them.

Thus, a package of efficiency initiatives with efficiency improvements in household energy use, and more competitive renewable energy production, is only one way to boost renewables use in the economy, reducing energy use from non-renewables, and driving the economy forward on a sustainable path. In other words, particular attention should be paid to all energy uses, both by producers and consumers.

Table 5. Percentage change in key macroeconomic indicators in Scenarios 4, 5 and 6

	10% increase in efficiency in petroleum consumption	Scenarios 1 and 4	Scenarios 1, 2 and 4
	Scenario 4	Scenario 5	Scenario 6
GDP (expenditure approach)	0.130	0.281	0.308
Total domestic output	0.017	0.073	0.118
Total Exports	-0.103	0.037	0.081
Total Imports	-0.243	-0.160	-0.127
Total private consumption	0.204	0.486	0.521
Unemployment	-0.460	-1.112	-1.229
Nominal wages	-0.118	-0.230	-0.214
Real wages	0.032	0.078	0.087
CPI	-0.151	-0.308	-0.300
Capital rental	0.183	0.348	0.379

Table SI3 of SI shows the rebound effects of Scenarios 4, 5, and 6. The sectoral rebound refers to petroleum use in households in Scenario 4. The household economy-wide rebound in sectoral use is greater after an improvement in household petroleum use than after improvement in household electricity use. There is, therefore, a lower reduction in energy use than in Scenario 1, that provokes rebound effects in all petroleum use in the economy, reaching 20.53%, in comparison with the 1.10% of Scenario 1. This is due to the weight of household fuel use in total energy that is more important than the household electricity use, because the use of electricity by industry is significant. Therefore, the proportionate reduction in all energy use in the economy is greater than the proportionate increase in efficiency, as in Scenario 1, due to it being an energy-intensive sector.

The combined effect of both improvements in household use encourages both household rebound effects and total rebound effects, in all energy use, in Scenarios 5 and 6. Note that two efficiency improvements are considered, so the level reaches 20%. Indeed, the implication of the package of all measures shows that the total economy-wide rebound in all energy use is 31.10%, rather than being negative. However, this rebound demonstrates that it ceases to be considered damaging, and is, in fact, beneficial, with a greater renewable energy use in the economy, as Figure 4 shows. Thus, the greater rebound effects observed in Scenario 6 indicate an increased use of renewables, proving that rebound effects can be considered beneficial.

6. Discussion and conclusions

In this paper, we analyse the rebound effects of a different forms of technological progresses impacting energy use, with the objective of finding the best combination to achieve a positive result through increased energy efficiency in household consumption, and through the production of more competitive electricity from renewable sources. We employ an energy-related CGE model that develops the inclusion of renewable energies for Spain, with a high level of detail for the energy and transport sectors both in the production and consumption functions. We simulate two kinds of efficiency scenario, based on increased energy efficiency in household consumption - focusing mainly on efficiency in electricity use, but later introducing efficiency in other fuel use - and then the production of more competitive electricity from renewable sources, by means of improvements in capital and labour productivity on the supply side.

Results show that technological progress reducing the role of non-renewable source in household electricity use (via demand) and more competitive renewables (via supply routes) will generate the co-benefit of expansionary processes being triggered across the wider Spanish economy with the analytical underpinnings having more generic applicability. Positive outcomes in this regard are observed notably in terms of employment - labour as a factor of production - and are induced by the switch in demand towards non-energy goods and services that, in turn, lead to increased supply of those goods, after the electricity saving and its corresponding income and substitution effects. The reduction in non-renewable electricity demand involves declines in all energy demands. Thus, energy production is reduced because of the contraction in demand, in line with prior results observed in the literature (Anson and Turner, 2009 and Turner, 2009). However, such reductions are not registered in petroleum use, also in line with prior findings in Cansino et al. (2019), what would require more efficient vehicles. More competitive renewable electricity production allows for increased penetration of renewable energies in the economy, although the consumption of non-renewable electricity and petroleum is increased in the absence of any further action to further induce or incentivise substitution away from these options.

Our results suggest that a policy approach involving a combination of measures to increase technological efficiency in household electricity use, combined with more competitive supply of renewable energies is likely to trigger and sustain a range of positive outcomes for the Spanish economy as a whole, again with the analytical underpinnings having more generic applicability. In the Spanish context, the targeted increase in renewable energy use in the overall economy is attained, while the use of non-renewables is markedly reduced, although, in the absence of any other action to affect the reliance on conventional vehicles and fuelling, the increase in petroleum consumption persists as a result of positive household income effects. However, we do evaluate the impacts of a basic increase in technical efficiency in petroleum use for household transportation that achieves reductions in use, thereby driving significant declines in petroleum production.

The analysis of the rebound effects gains policy relevance in the context of what are often primary policy objectives in reducing energy use. Our results demonstrate that increased efficiency in household non-renewable electricity use, with more competitive renewable electricity production, involves a greater overall reduction in household use of electricity. Moreover, there is a reallocation in the use of energy towards renewables. More interestingly, negative rebound results are obtained due to larger falls in total energy use than the proportionate increase in efficiency. As noted, this confirms the importance of the components of the energy mix, and its potential reallocations. Additionally, these results reveal the intensity of the electricity sector that is significantly affected by the efficiency improvements in household electricity use. Different analyses are found in the literature to explain negative rebound effects, such as Saunders (2008) and Turner (2009).

Finally, our analyses suggest that a package of improvements in electricity and petroleum household use can achieve reductions in all energy uses, with related positive outcomes for the economy as a whole, due to the stimulus triggered in demand in non-electricity and petroleum goods when energy spending requirements are reduced. In our Spanish context, this scenario achieves the penetration targeted for renewables in the total energy use, combined with reductions of non-renewables. Of course, this is only one of several ways to boost renewables use in the economy through developing a policy focus on reducing the use of non-renewable sources and driving the economy forward on a sustainable path.

The insights of this research highlight a need for politicians and decision makers to focus attention on all energy uses, with measures and strategies designed to reduce and improve the use of electricity in households and, at the same time, devise strategies to achieve improvements in transport uses. Moreover, our results highlight the need for improved competitiveness in renewable energy supply relative to non-renewable supplies. However, this highlights a need for policy actions and/or support mechanisms that enable citizens and firms to implement technologies to take advantage of renewables in all energy uses, and use non-renewable energies in a more efficient way.

Regarding future lines of research, we are working on the development of a multiregional dynamic CGE model for all the countries of the European Union, which will include a high level of disaggregation of the current energy mix between renewable and non-renewable energies. The objective is to study the gradual adaptation and implementation of these regions to attain a just and clean energy transition towards 2050 through the compatibility of sustainable objectives. This natural extension would make it possible to study the role of renewables and evaluate their gradual evolution during the transitional period until 2050, such as a mechanism to reduce emissions to reach the EU climate strategy restrictions, remaining aware of the potential rebound effects in the transition towards the complete penetration of renewables in the total energy use, as is shown in this study.

Acknowledgements

The authors gratefully thank the anonymous reviewers for their interesting and constructive comments and recommendations which definitely helped to improve the article.

Funding: Karen Turner acknowledges support from the UK Engineering and Physical Sciences Research Council (EPSRC grant ref. EP/M00760X/1) in undertaking the research reported here.

References

Abdulwakil, M.M, Abdul-Rahim, A.S., Alsaleh (2020) Bioenergy efficiency change and its determinants in EU-28 region: Evidence using Least Square Dummy Variable corrected estimation, *Biomass and Bioenergy*, 137, 105569. DOI: 10.1016/j.biombioe.2020.105569

Allan, G.J., Hanley, N.D., McGregor, P.G., Swales, J.K., Turner, K.R., (2007) The impact of increased efficiency in the industrial use of energy: a computable general equilibrium analysis for the United Kingdom. *Energy Economics* 29, 779–798. DOI: 10.1016/j.eneco.2006.12.006

Alsaleh, M., Abdul-Rahim, A.s., Mohd-Shahwahid, H.O. (2017) Determinants of technical efficiency in the bioenergy industry in the EU28 region, *Renewable and Sustainable Energy Reviews*, 78, 1331-1349. DOI: 10.1016/j.rser.2017.04.049

Anson, S., Turner, K. (2009) Rebound and disinvestment effects in refined oil consumption and supply resulting from an increase in energy efficiency in the Scottish commercial transport sector, *Energy Policy*, 37(9), 3608-3620. DOI: 10.1016/j.enpol.2009.04.035

Brockway, P., Sorrell, S., Semieniuk, G., Heun, M.K., Court, V., (2021) Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications, *Renewable and Sustainable Energy Reviews*, 141, 110781. DOI: 9443/10.1016/j.rser.2021.110781

Burniaux, J., Truong, T., (2002) GTAP-E: An Energy-Environmental Version of the GTAP Model. GTAP Technical (Paper no. 16, Center for Global Trade Analysis, Purdue University, West Lafayette, IN).

Cai, Y., Aora, V., (2015) Disaggregating electricity generation technologies in CGE models: A revised technology bundle approach with an application to the U.S. Clean Power Plan, *Applied Energy*, 154, 543-555. DOI: 10.1016/j.apenergy.2015.05.041

Cámara, A., Flores, M., Fuertes, P., (2013) A Social Accounting Matrix to analyze the renewable energy sector, Estadística Española, 55(181), 149-176.

Cansino, J.M., Román-Collado, R., Merchán, J. (2019) Do Spanish energy efficiency actions trigger JEVON'S paradox?, *Energy*, 181, 760-770.

Chi, Y., Guo, Z., Zheng, Y., Zhang, X. (2014) Scenarios analysis of the energies' consumption and carbon emissions in China based on a dynamic CGE model, *Sustainability*, 6, 487-512.

De Melo, J. Tarr, D., (1992) A General Equilibrium Analysis of US Foreign Trade Policy. Cambridge, MA, The MIT Press.

Duarte, R., Rebahi, S., Sánchez-Chóliz, J., Sarasa, C., (2014) Households' behaviour and environmental emissions in a regional economy. *Economic Systems Research*, 26(4), 410-430. DOI: 10.1080/09535314.2014.903231

Du, H., Chen, Z., Zhang, Z, Southworth, F. (2020) The rebound effect on energy efficiency improvements in China's transportation sector: A CGE analysis, *Journal of Management Science and Engineering*, 5, 249-263. DOI: 10.1016/j.jmse.2020.10.005

Duarte, R., Feng, K., Hubacek, K., Sánchez-Chóliz, J., Sarasa, C., Sun, L., (2016) Modeling carbon consequences of pro-environmental behaviors of consumers in Spain. *Applied Energy*, 184, 1207-1216. DOI: 10.1016/j.apenergy.2015.09.101

Duarte, R., Sánchez-Chóliz, J., Sarasa, C., (2018) Consumer-side actions in a low-carbon economy: A dynamic CGE analysis for Spain. *Energy Policy*, 118, 199-210. DOI: 10.1016/j.enpol.2018.03.065

European Commission (2017). Climate strategies and targets. European Commission. Brussels, Belgium.

Eurostat (2017) % Energy dependence, European Commission, Brussels, Belgium.

EU SDS (2009) European Union Sustainable Development Strategy, Brussel, Belgium.

Figus, G., Turner, K., McGregor, P., Katris, A. (2017). Making the case for supporting broad energy efficiency programmes impacts on household incomes and other economic benefits. *Energy Policy* 111, 157–165. DOI: 10.1016/j.enpol.2017.09.028

Figus, G., McGregor, P.G., Swales, K., Turner, K. (2020) Do sticky energy prices impact the time paths of rebound effects associated with energy efficiency actions? *Energy Economics*, 86, 104657. DOI: 10.1016/j.eneco.2019.104657

Hertel, T.W. (1997) Global Trade Analysis. Modelling and Applications. Cambridge, Cambridge University Press.

IDAE. (2010) The Annual Report of Energy Consumption, 2010. Institute for diversification and energy saving, Ministry of Industry, Tourism and Trade, Madrid, Spain.

IPCC (2014) Climate Change 2014: Mitigation of Climate Change, Intergovernmental panel on climate change, fifth assessment report.

Jevons,W.S. (1865) *The Coal Question: Can Britain Survive?* London, Macmillan. Khazzoom D.J. (1987) Energy Saving Resulting from the Adoption of More Efficient Appliances. *The Energy Journal*, 8, 85–89.

Khoshkalam Khosroshahi, M., Sayadi, M. (2020). Tracking the sources of rebound effect resulting from the efficiency improvement in petrol, diesel, natural gas and electricity consumption; A CGE analysis for Iran, *Energy*, 197, 117-134.

Koesler, S., Swales, S., Turner, K., (2016). International spillover and rebound effects from increased energy efficiency in Germany, *Energy Economics*, 54, 444-452. DOI: 10.1016/j.eneco.2015.12.011

Lecca, P., McGregor, P.G., Swales, J.K., Turner, K., (2014) The added value from a general equilibrium analysis of increased efficiency in household energy use. *Ecological Economics*. 100, 51–62. DOI: 10.1016/j.ecolecon.2014.01.008

Lekavicius, V., Galinis, A., Miskinis, V. (2019) Long-term economic impacts of energy development scenarios: The role of domestic electricity generation, *Applied Energy*, 253, 113527. DOI: 10.1016/j.apenergy.2019.113527

Liu, X., L. Bohlin (2012) Effects from consistent internalization of external effects from transport and manufacturing – a CGE analysis for Sweden, Working Paper 09/2012, Swedish Business School. ISSN 1403-0586.

Mainar, A. (2010), Consumption Patterns and Environmental Impacts of the CO2, Emissions, An Approximation from Input-Output Analysis. Ph. D. thesis, Dep. of Econ. Analysis, Univ. of Zaragoza, Zaragoza, Spain.

MINETUR (2010) The energy in Spain. Secretary of Energy State, Ministry of Industry, Tourism and Trade, Madrid, Spain.

NECPs (2018) The national energy and climate plans, European Commission, Brussels.

NSI (2010) Input-Output Framework 2010, National Statistics Institute, Madrid, Spain, 2010.

RED (2009). Renewable Energy Directive 2009/28/CE. European Commission, Brussels, Belgium.

RED II (2018). Promotion of the use of energy from renewable sources Amendments adopted by the European Parliament on 17 January 2018 on the proposal for a directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources.

REN21 (2017) Renewables 2017. Global Status Report. Paris, France.

Saunders, H.D. (2008) Fuel conserving (and using) production functions. *Energy Economics* 30, 2184–2235. DOI: 10.1016/j.eneco.2007.11.006

SEI (2019) The Production Gap Report. Stockholm Environment Institute. Stockholm (Sweden)

Sorrell, S. (2007) The Rebound Effect: An Assessment of the Evidence for Economy-wide Energy Savings From Improved Energy Efficiency, Technical Report. UK Energy Research Centre, London, United Kingdom.

Sorrell S, Dimitropoulos J, Sommerville M., (2009) Empirical estimates of direct rebound effects. *Energy Policy*; 37:1356–7. DOI: 10.1016/j.enpol.2008.11.026

Sue Wing I., (2006) The synthesis of bottom-up and top-down approaches to climate policy modeling: electric power technologies and the cost of limiting US CO2 emissions. *Energy Policy*, 34, 3847–69. DOI: 10.1016/j.enpol.2005.08.027

Sue Wing I,. (2008) The synthesis of bottom-up and top-down approaches to climate policy modeling: electric power technology detail in a social accounting framework*,* *Energy Economics*, 30, 547–73. DOI: 10.1016/j.eneco.2006.06.004

Timilsina, G.R., Mevel, S., Shrestha, A. (2011) Oil price, biofuels and food supply. *Energy Policy,* 39, 8098–8105.

Turner, K., (2009). Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK Economy, *Energy Economics*, 31(5) 648-666. DOI: 10.1016/j.eneco.2009.01.008

Turner, K., (2013) Rebound effects from increased energy efficiency: a time to pause and reflect? *The Energy Journal*, 34 (4), 25–42.

Van den Bergh, J., (2011) Energy conservation more effective with rebound policy. Environ. Resour. Econ. 48 (1), 43–58. DOI: 10.1007/s10640-010-9396-z

Supplementary Information

Table SI1. Elasticity parameters used in the model

Substitution elasticity between:	
Labour and Capital-Energy aggregate (KLE)[a]	$\sigma^{KLE} = 0$ - 0.9
Capital and Energy aggregate (KE)[a]	σ^{KE} = 0.1 - 0.9
Energy ad transport services [a]	σ^{EF} = 0.6
Electricity and Fossil Fuels aggregate [a]	σ^{FFE} = 0.5 - 1
Coal and Oil-Gas aggregate [a]	σ^{CG} = 0 – 1
Oil and Gas [a]	σ^{OG} = 0 - 1
Oil and Biofuel [b]	σ^{OB} = 2.4
Non-renewable and clean power [c]	σ^{RE} = 0.5 - 2
Renewable Energies [d]	σ^{RE} = 1 - 2
Transport services [e]	σ^{TRT} = 0
Air and Sea [e]	σ^{AS} = 0
Domestic and import goods [f]	σ^{A}= 1.9 - 3
Demand elasticity coefficients [g]	σ^{C}= 0.2-0.5
Transformation elasticity between:	
Exports and domestic goods[h]	σ^{T}= 0.7 - 3.9

[a] Elasticity values by sectors from Burniaux and Truong (2002).

[b] Timilsina et a. (2011)

[c] Chi et al., (2002)

[d] Anson and Turner (2009)

[e] Liu and Bohlin (2012)

[f] Armington elasticities from Hertel (1997). Trade elasticities of renewable and non-renewable electricity are set at 5.0 following Anson and Turner (2009) to reflect the homogeneity of electricity from different sources.

[g] Mainar (2010).

[h] De Melo and Tarr (1992).

Table SI2. Changes in price by sectors

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Agriculture and livestock	0.095	0.020	0.115	0.107	0.202	0.221
Forestry	0.061	0.023	0.083	0.069	0.130	0.153
Fisheries	-0.004	0.009	0.005	-0.002	-0.006	0.004
Coal	0.004	-0.001	0.003	0.005	0.010	0.009
Petroleum	0.006	-0.001	0.004	0.007	0.013	0.011
Electricity non-renewable	0.053	-0.282	-0.229	0.061	0.114	-0.169
Gas	0.076	0.014	0.090	0.084	0.160	0.174
Wind	0.037	-2.643	-2.610	0.043	0.080	-2.571
Hydropower	0.051	-2.905	-2.859	0.059	0.110	-2.805
Solar	0.015	-2.677	-2.664	0.019	0.034	-2.647
Biomass	0.005	-0.179	-0.174	0.008	0.012	-0.167
Biofuels	0.001	-0.075	-0.074	0.003	0.004	-0.071
Water	0.011	0.006	0.017	0.015	0.026	0.032
Agri-food industry, beverages and tobacco	0.043	0.010	0.053	0.050	0.093	0.103
Textiles	0.011	0.004	0.015	0.014	0.025	0.029
Wood	-0.005	0.003	-0.002	-0.002	-0.007	-0.004
Paper	0.000	0.001	0.001	0.004	0.004	0.005
Chemicals	0.000	-0.002	-0.002	0.002	0.003	0.000
Construction materials	0.004	-0.007	-0.002	0.008	0.012	0.005
Metallurgy	-0.001	-0.019	-0.019	0.002	0.001	-0.017
Basic metals	-0.023	-0.005	-0.027	-0.021	-0.044	-0.048
Equipment	-0.003	0.001	-0.002	-0.001	-0.005	-0.003
Manufacture of motor vehicles and trailers	-0.011	-0.003	-0.014	-0.008	-0.019	-0.022
Other transport material	-0.022	0.004	-0.018	-0.021	-0.043	-0.039
Furniture	-0.009	0.004	-0.005	-0.007	-0.016	-0.012
Construction	0.009	0.010	0.019	0.013	0.022	0.032
Commercial services	0.006	0.011	0.017	0.010	0.016	0.027
Land transport services	0.009	0.011	0.020	0.014	0.023	0.034
Shipping services and inland waterways	0.058	0.021	0.079	0.068	0.127	0.147
Air transport services	0.009	0.016	0.025	0.014	0.023	0.039
Other transport services	0.000	0.011	0.011	0.003	0.004	0.014
Hotels and restaurants	0.035	0.016	0.051	0.041	0.076	0.092
Communications	0.028	0.014	0.042	0.034	0.063	0.076
Credit and insurance	0.019	0.019	0.038	0.024	0.043	0.063
Real estate agencies	0.119	0.025	0.144	0.133	0.252	0.277
Public services	-0.032	0.013	-0.018	-0.031	-0.063	-0.049
Education	-0.073	0.013	-0.059	-0.076	-0.148	-0.135
Health	-0.039	0.013	-0.026	-0.039	-0.078	-0.065
Other services	-0.003	0.015	0.012	0.000	-0.003	0.013

Table SI3. Economy-wide rebound effects

$\boldsymbol{R = \left[1 + \frac{\dot{E}}{\propto\gamma}\right]100}$	**Scenario 1**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
$\dot{E}$ (Change in HH electricity use)	-0.07748	-0.07689	-0.06819		
Efficiency improvement	0.10	0.10	0.10		
Rebound	**22.52**	**23.11**	**31.81**	**n.a**	**n.a**
$\dot{E}$ (Change in HH total energy use)	-0.03688	-0.03653	-0.02805	-0.06508	-0.06475
Efficiency improvement	0.10	0.10	0.10	0.20	0.20
Share (HH total electricity (or petroleum) use / HH total energy use)	0.43287	0.43287	0.42840	0.86127	0.86127
Rebound	**14.81**	**15.61**	**34.53**	**62.22**	**62.41**
$\dot{E}$ (Change in total electricity use ind+hh)	-0.02110	-0.02113	-0.03024		
Efficiency improvement	0.10	0.10	0.10		
Share (HH use elect / Total use of electricity (ind+HH))	0.21337	0.21337	0.38058		
Rebound	**1.10**	**0.96**	**20.53**	**n.a**	**n.a**
$\dot{E}$ (Change in total energy use (hh + ind))	-0.012092	-0.011296	-0.010135	-0.022284	-0.021492
Efficiency improvement	0.10	0.10	0.10	0.20	0.20
Share (HH total elect / Total energy use (hh+ind))	0.079542	0.079542	0.078721	0.158263	0.158263
Rebound	**-52.01**	**-42.01**	**-28.75**	**29.60**	**32.10**