

Freire-González, Jaume; Ho, Mun S.

Article — Accepted Manuscript (Postprint)

Voluntary actions in households and climate change mitigation

Journal of Cleaner Production

Suggested Citation: Freire-González, Jaume; Ho, Mun S. (2021) : Voluntary actions in households and climate change mitigation, Journal of Cleaner Production, Elsevier BV, Amsterdam, Vol. 321, <https://doi.org/10.1016/j.jclepro.2021.128930>

This Version is available at:

<https://hdl.handle.net/10419/314408>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.

Voluntary Actions in Households and Climate Change Mitigation

Jaume Freire-González ^{a,1}, Mun S. Ho ^b

^aENT Foundation, Josep Llanza, 1-7, 2 3, 08800, Vilanova i la Geltrú, Barcelona.

^bHarvard China Project on Energy, Economy and Environment, SEAS, Harvard University, Cambridge, MA 02138, USA.

This paper is a postprint of an article published by the Journal of Cleaner Production, first posted on 7 September 2021 as <https://doi.org/10.1016/j.jclepro.2021.128930>, and later published in Volume 321, Number 25, October, 128930.

Abstract

Governments foster voluntary actions within households to mitigate climate change. However, the literature suggests that they may not be as effective as expected due to rebound effects. We use a dynamic economy–energy–environment computable general equilibrium (CGE) model of the Catalan economy to simulate the effect of 75 different actions on GDP and net CO₂ emissions, over a 20-year period. We also examine how a carbon tax could counteract the carbon rebound effects. We find energy rebound effects ranging from 61.77% to 117.49% for voluntary energy conservation actions, depending on where the spending is redirected, with similar carbon rebound values. In our main scenarios, where energy savings are redirected to savings and all non-energy goods proportionally, the rebound is between 64.47% and 66.90%. We also find, for these scenarios, that a carbon tax of between 2.4 and 3.6 €/ton per percentage point of voluntary energy reduction would totally offset carbon rebound effects. These results suggest that voluntary actions in households need additional measures to provide the expected results in terms of energy use reduction and climate change mitigation.

Keywords

Voluntary actions, climate change, rebound effect, computable general equilibrium, carbon tax.

¹ Corresponding author.

E-mail address: jfreire@ent.cat.

1. Introduction

Voluntary actions within households or changes in consumption patterns to reduce carbon emissions are usually fostered by governments and other institutions, as they are seen as an inexpensive but effective way to reduce carbon emissions and therefore mitigate climate change. These include actions such as using more efficient lighting, buying energy-saving household equipment, changing packaging and changing diets. However, consciously or not, these actions lead to a reallocation of resources to other goods and services or to savings, or a combination of both. Depending on the energy (or carbon) intensity of this reallocated spending, the action can end up triggering rebound effects (Sorrell, 2007), reducing or counteracting the expected reduction in emissions. The analysis of different potential ways these freed resources can be used is known in the rebound effect literature as re-spending modelling (Freire-González, 2011). When these actions end up with an increase of energy use, the effect is known as the Khazzoom-Brookes postulate or the Jevons' Paradox (Saunders, 1992). This problem extends to other natural resources, not just energy (Font Vivanco et al., 2016a).

Focusing on voluntary actions within households, van den Bergh (2011) points out that, although energy conservation seems to be an inexpensive way to realize environmental and energy-climate goals, it overlooks the rebound phenomenon. Some studies have empirically assessed this issue, using different modelling frameworks and assumptions. Alfredsson (2004), using hybrid input–output methods in a study for Swedish households, found that adopting “green” consumption patterns did not reduce carbon emissions as expected, and even increased them in some cases. Druckman et al. (2011), also using hybrid input–output methods, estimated a rebound effect for a combination of three abatement actions by UK households of 34%. Targeting re-spending on goods and services with a low greenhouse gas (GHG) intensity found a rebound of around 12%, while re-spending on goods and services with a high GHG intensity was found to backfire. Murray (2011) estimated a rebound effect of 5% from electricity conservation actions in households in Australia. Later, Murray (2013) found rebound effects of 4–24% for electricity and motor fuel conservation, using household demand models with life-cycle analysis (LCA) methodologies. Bjelle et al. (2018), using environmentally extended input–output methods, found rebound effects of 40–59% for Norwegian households.

Finally, a recent literature review of energy sufficiency and rebound effects by Sorrell et al. (2020; p. 8) states that “rebound effects tend to be modest (e.g. 5 to 15%) for energy sufficiency actions affecting heating and electricity, larger (e.g. 15 to 50%) for actions affecting transport fuels and very large (e.g. 50 to >100%) for actions affecting food consumption.” However, as these authors suggest, there are no studies using CGE modelling methods to determine rebound effects from voluntary conservation actions within households. CGE models which account for inter-industry interactions are widely used for energy and climate policy assessments (Beckman et al., 2011; Babatunde et al., 2017). They simulate changes in industry prices and quantities due to policy shocks by including general equilibrium effects. They can include more complex behavioural equations of the economic agents than other approaches using fixed coefficients, like input-output analysis. Tracking the general equilibrium and inter-industry effects are important for estimating rebounds from sufficiency policies, conservation or voluntary actions. The studies of carbon prices using CGE model simulations often discuss the size of leakage, that is, how the rise in emissions in non-policy countries offset the reduction in the countries with a carbon price (e.g., Böhringer et al., 2012). Our simulation of rebound effects here are in the same spirit.

It is also important to point out that in the last decade, some researchers have started to analyse possible solutions to achieve the full potential of these kinds of actions (van den Bergh, 2011; Freire-González and Puig-Ventosa, 2015; van den Bergh, 2015; Font Vivanco et al., 2016b; Freire-González, 2020). However, the evidence on different measures to offset rebound effects is still scarce and scattered.

The main objective of this study is to comprehensively test the efficacy of changes in households’ preferences in mitigating climate change, changes that may arise from voluntary actions. Economy-wide energy and carbon rebound effects are obtained. We also examine how a carbon tax may be added to these voluntary actions to offset the rebound effects. A recursive-dynamic economy–energy–environment CGE model for the Catalan economy is used, and a set of 75 different actions (or scenarios), with a total of 1,560 runs, is tested. Additionally, for the main scenarios, the carbon tax needed to counteract the triggered rebound effects is assessed. No other study provides such detail and comprehensiveness, nor is there another study that uses this methodology for this purpose.

The article is structured as follows: Section 2 contains a description of the methodology used in this study including the model, the data sources used in the development of the social accounting matrix (SAM), the parameters, exogenous variables and the calibration process, and the different scenarios simulated. Section 3 summarizes the main results of the research. Finally, Section 4 gives the main conclusions. Additionally, the full set of equations of the model can be found in Appendix I, while different elasticities can be found in Appendix II. Appendix III contains tables with details on the main results in terms of GDP variations, CO₂ variations and energy rebound effects.

2. Methodology

We constructed a recursive-dynamic economy–energy–environment CGE model for the Catalan economy covering 65 sectors to simulate the impact of shifts in household preferences. This section first gives a general description of the model. Previous different versions of this model can be found in Freire-González and Ho (2019), and a version for China was used in Cao et al. (2019) to simulate an emission trading system. However, the version we use here has several specific features described in detail in Appendix I. These have been developed due to the specific target of this research and the specific features of the Catalan economy. The model is coded in GAMS, using CONOPT4 and PATHNLP solvers to run simulations. After describing the model, we discuss the data and the policy scenarios.

Figure 1 shows our methodology in a flow diagram with a summary of the key aspects of the CGE model.

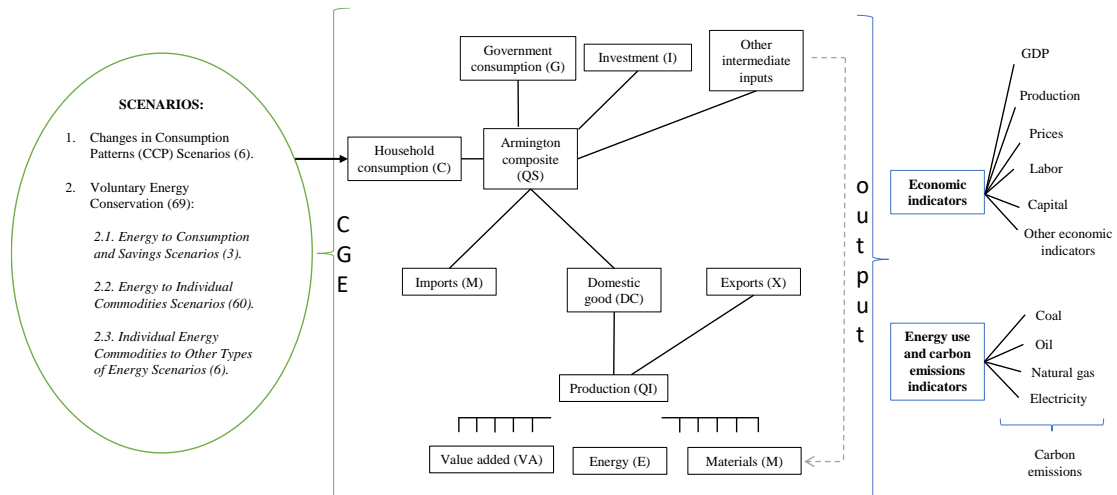


Fig. 1. Flow diagram for the overall methodology (steps involved).

2.1. Agents in model

The model describes the economic behaviour of four main agents in the economy: households, firms, government and the foreign sector. They have different economic roles which are represented by different behavioural (supply and demand) functions (see Appendix I for detail). A summary of the economic flows among them is shown in Table 1. Each entry represents payments from economic agents in columns to sectors in rows.

Table 1. Summary of the economic flows represented in the model by behavioural equations, from agents (columns) to agents (rows).

	Households	Firms	Government	Rest of the world
Households		- Wages and salaries. - Dividends.	- Transfers. - Subsidies. - Interest on bonds.	- Transfers.
Firms	- Purchase of goods and services.	- Purchase of intermediate goods and services	- Purchase of goods and services. - Transfers. - Subsidies. - Interest on bonds.	- Purchase of exports. - Transfers.
Government	- Taxes and fees. - Social security contributions.	- Taxes and fees. - Social security contributions.		- Tariffs, taxes and fees. - Transfers.
Rest of the world	- Purchase of imports. - Transfers.	- Purchase of imports. - Dividends. - Transfers.	- Purchase of imports. - Transfers. - Interest on bonds.	
<i>Capital account</i>	- Savings/debt.	- Retained earnings/debt.	- Savings/debt.	- Current account.

Source: Own elaboration.

The model assumes markets are competitive with constant returns to scale, which implies there are no profits for firms. If there are no profits, the price of output is equal to the unit costs of firms. Labour and capital are mobile across industries in each period.

2.2. Production

Production is represented by a nested structure of constant elasticity of substitution (CES) and Cobb-Douglas functions, as shown in Figure 2. At the lower level of the nested structure, value added (VA) is described by combining capital (K), labour (L) and land (T) using CES functions. At the same level, the energy composite (E) is formed from four energy inputs, also using a CES function. At a higher level, the value added-energy composite (VE) is a CES function of VA and E. At this same level, aggregate non-energy intermediate input (M) is a Cobb-Douglas function of all the other intermediate commodities. Finally, the top level combines the capital-labour-land-energy composite (VE) with the non-energy intermediate composite using a CES production function and delivering the output of each industry (QI). There is Hicks-neutral total productivity growth, that is, energy input per unit output falls together with other inputs; we assume there is no biased technical change.

Biased technical change, such as improvements in energy intensities that are not due to price effects, play an important role in baseline energy use and emissions. However, we are focused on rebound effects due to policy or behavioural shocks. We perform sensitivity analyses of alternative assumptions of changes in energy intensities (often called the autonomous energy efficiency improvement, AEEI) to show that these have only minor effects on rebound rates in section 3.2.4.

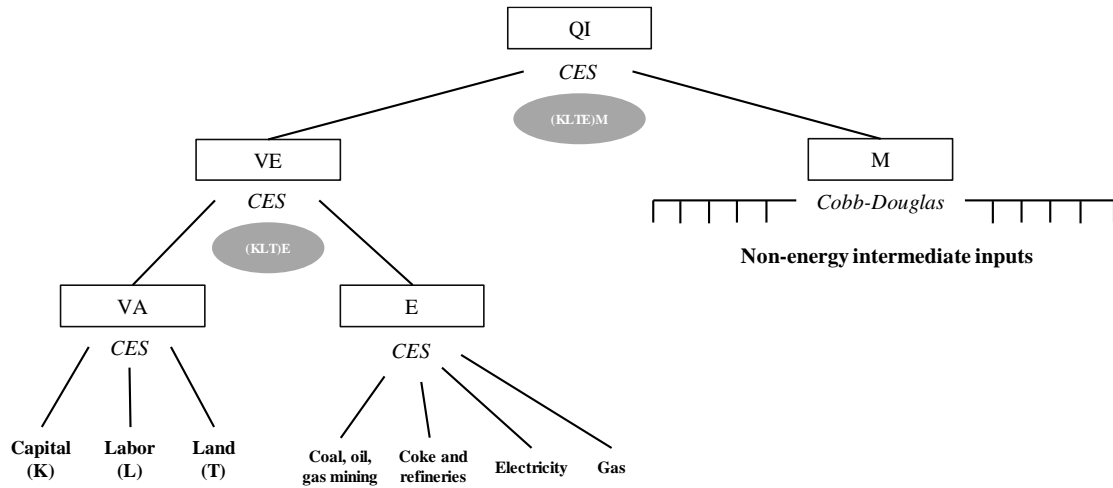


Fig. 2. Production structure for each industry in the Catalan economy–energy–environment CGE model.

2.3. Trade

This is a single-country model and has an import demand function and another function to allocate domestically produced commodities between the domestic market and exports. The share of exports depends on domestic prices relative to the rest of the world prices, and export supply falls with rising domestic prices. The domestic supply of commodities follows the Armington (1969) approach, that is, total supply is a CES function of domestically produced goods (DC) and imported (M) imperfect substitutes. On the other side, the allocation of domestically produced commodities between domestic commodities (DC) and exports follows a constant elasticity of transformation (CET) function. Figure 3 shows the structure of the trade module and its interaction with the production structure of the model.

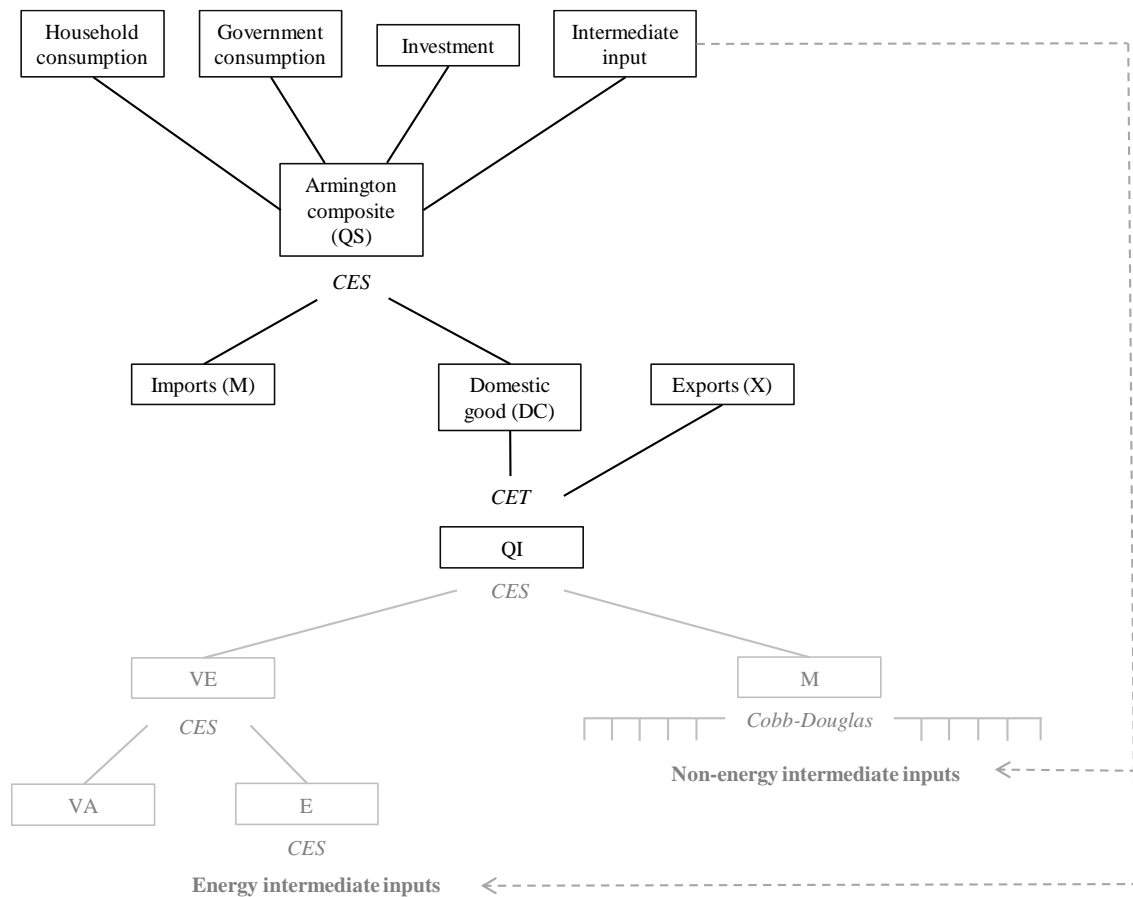


Fig. 3. Consumption and trade structure of the Catalan recursive-dynamic economy–energy–environment CGE model.

2.4. Energy and CO2 emissions

The model contains an energy and carbon emissions module. Economic flows for energy sectors and commodities in euros are described through the supply and use (input–output)

tables. In order to transform these monetary flows into energy and carbon units, we use three coefficients: 1) quantity coefficients transform the monetary flows of energy products in physical flows (million tons of coal per million €); 2) energy coefficients transform the quantity of energy products to energy units (exajoules per million tons); and 3) carbon coefficients transform energy units to carbon emissions units (million tons of CO₂ per exajoule). These coefficients are described in detail in Appendix I and we assume they are stable during the period of analysis. Additionally, we also account for process CO₂ emissions and have a coefficient that transforms production of cement in euros into carbon emissions.² The coefficients for the power generation sector are obtained from the total emissions from electricity in Catalonia (from the Catalan Office of Climate Change) and the total electricity use (from the Catalan Energy Institute (ICAEN)). For imports we use the same coefficient, assuming a similar energy mix in electricity imports. The model includes the actual percentage of renewables for 2014-2017, and this share is then simply projected using a logarithmic function using the sample period data.³ If renewables grow faster than this projection, then the carbon rebound effect may be overestimated for shocks involving reductions in electricity use, but not the energy rebound effect. The same accounting method is used in Freire-González and Ho (2018; 2019).

A change in economic conditions, following a policy or an exogenous shock, will change flows of energy in the entire input–output system, triggering changes in total energy use and carbon emissions.

2.5. Dynamics

The model is a Solow-type economic growth model, where the output growth is driven by capital accumulation, population growth and total factor productivity (TFP) growth. It is recursive, as investment is determined by an exogenous savings rate obtained from the SAM, and capital stock at the end of a period is equal to capital stock of the previous period, less depreciation, plus the investment of the period (equation A52 in Appendix I).

² This coefficient represents the average over the various cement products in the Non-metallic mineral products industry in the base year and is assumed constant in the projection period, that is, the composition of the various products is assumed fixed.

³ The resulting equation is $y = 0.0127 \ln(x) + 0.3272$, with an R^2 of 0.93. In 10 years' time, the renewable share rises from 0.328 to 0.358.

2.6. Data

The Social Accounting Matrix

There are different sources of data used in this study. The core of the data is the SAM for the Catalan economy for 2014 that we developed to parameterize the model. Its input–output section is a square matrix with 64 industries/commodities, and it includes information for the four different agents considered: households, firms, government and rest of the world. It has a total of 148 rows/columns when we combine the supply and use quadrants. Table 1 shows a summary of the Catalan SAM.

The necessary data to develop the SAM are collected from various sources. Supply and use tables for 2014 for Catalonia were obtained from the input–output accounts from the Statistical Institute of Catalonia, as well as the rest of the world accounts. Government accounts, including social security accounts, are from the Ministry of the Vice-presidency of the Economy and Finance of Catalonia and from the General Comptroller of the State Administration of Spain (IGAE). Data on the stock of capital came from the BBVA Foundation (Mas Ivars et al., 2018), while firms’ accounts have been obtained from the Bank of Spain. Data on industry-level employment are obtained from the input–output framework for Catalonia 2014, as well as labour and capital compensation.

After collecting all these data, a calibration process homogenizes and consolidates the values from different sources and generates a balanced square matrix. The RAS method is used to adjust values and balance some row and column elements of the SAM.

Table 2. Summary of the Catalan SAM 2014, in Million Euros.

	Commodity	Industry	Labour	Capital	Land	Households	Enterprise	Government	Taxes Less Subs. on Products	Other Taxes on Prods.	Social Security	Tariffs	VAT for Import	Capital A/C	Rest of World	TOTAL
Commodity		215,357.0				112,278.5		32,463.3						35,979.0	138,824.4	534,902.2
Industry	417,720.6															417,720.6
Labour		104,064.0														104,064.0
Capital		82,256.6														82,256.6
Land		1,335.4														1,335.4
Households			80,279.0		1,335.4		67,797.1	12,345.9								161,757.4
Enterprise				81,820.6												81,820.6
Government				436.1		23,297.3	10,670.1		11,755.9	2,951.7	23,785.0	276.0	4,212.6	-8,406.6		68,978.1
Taxes Less Subs. on Products		11,755.9														11,755.9
Other Taxes on Prods.		2,951.7														2,951.7
Social Security			23,785.0													23,785.0
Tariff	276.0															276.0
VAT for Import	4,212.6															4,212.6
Capital A/C						26,181.6	3,353.5	1,708.3							-3,670.9	27,572.5
Rest of World	112,692.9							22,460.6								135,153.5
TOTAL	534,902.1	417,720.6	104,064.0	82,256.6	1,335.4	161,757.3	81,820.6	68,978.0	11,755.9	2,951.7	23,785.0	276.0	4,212.6	27,572.4	135,153.5	

Energy and CO₂ Emissions Data

The energy and CO₂ emissions module of the model is calibrated with actual data on energy commodities. As explained in Section 2.4, this module transforms the euro value of consumption of these commodities into quantities of energy products, total energy used and, finally, into carbon emissions released into the environment.

Data on the consumption of coal, oil, natural gas and electricity were collected from energy balances for Catalonia for 2014 from the Catalan Energy Institute (ICAEN). They contain detailed data of the supply and consumption of energy. Energy and carbon emissions coefficients were obtained from the International Energy Agency (IEA); These conversion factors transform 1 ton of coal, oil or 1 m³ of natural gas into energy units (Gigajoules). An average quantity coefficient for all industries has been used because there is no information on the individual industry use of the different energy commodities. This simplification is not a major concern for our purpose of analysing changes in consumption behaviour.

Parameters and Exogenous Variables

Along with the SAM and the energy and environmental data, other pieces of information, including parameters and projected exogenous variables, are also used in the model. A key aspect in CGE models is the choice of different elasticities in the CES and CET functions. Appendix II shows the different elasticity values chosen in different functions and their data sources.

The input share parameters in the production functions are obtained from the Use table part of the SAM. We keep these shares unchanged for all periods in the simulations, assuming stability in production structure in the base case. Similarly, the share parameters of the final consumption functions of households, government purchases and investment were obtained from the SAM, and kept constant for all years of analysis. When we specify shifts in consumption and investment patterns, we adjust these share parameters in the policy cases (α_{it}^c in Appendix eq. A29).

The exogenous variables in the model are population, saving rates, dividend payout rates, current account deficits and government deficits. The projections of the population are from the Statistical Institute of Catalonia; we assume that the labour force grows at the same rate as total population. The other exogenous variables are obtained from the SAM and kept constant over the simulation period for simplicity, as their evolution is uncertain. The rate of total factor productivity growth is also exogenous and assumed the same for all industries. We calibrate the TFP growth rate so that the gross domestic product (GDP) growth averages 2% per year over the simulation horizon.⁴

Calibration of Comparison of Base Case and Policy Scenarios

The base case path is simulated with the parameters and exogenous variables just described. In the scenarios for changes in consumption patterns discussed next in Section 2.7, we will be shocking some of the parameters in the household consumption function and then simulating a new equilibrium path for the economy. Key variables from the policy path are compared with those obtained in the base case to show the impact of the tested policies. For each model run a complete set of macroeconomic aggregate and sectoral indicators is provided, as well as total energy use and CO₂ emissions. The base case and the defined scenarios are modelled for 20 years.

2.7. Scenarios

We are going to assess the effects of shifts in spending among different commodities. 64 commodities are identified in our model, four are energy related: (1) raw energy products, (2) coke and oil refining products, (3) electricity production and distribution services, and (4) manufactured gas and gaseous fuel distribution services. We will refer to the other 60 as the “other non-energy commodities.” In order to capture most of the potential effects of voluntary actions in households on carbon emissions, we designed two groups of scenarios. (1) The first group is focused on general changes in consumption patterns where we examine shifts among six broad consumption baskets. (2) The second group explores the effects of voluntary energy conservation at a finer level of commodity detail, how households reallocate spending from energy goods and services to other commodities. Here we consider four

⁴ The average interannual GDP growth of Catalonia in 2000-2019 was 1.9%, and we use 2% as a simple baseline.

subgroups of scenarios: (i) consumption shift from the 4 energy commodities to other non-energy commodities; (ii) consumption shift from energy to savings; (iii) consumption shift from energy to both other commodities and savings; (iv) consumption shift from some types of energy to other types. These scenarios are compared with the base case path with the original parameter values.

In all cases, only changes in consumption patterns have been simulated, transferring final demand expenditures from some commodities to other commodities, either directly, or indirectly when incomes are transferred to savings which then go to investment demand. The total income of households that is allocated to consumption and savings may change a little due to general equilibrium effects. That is, for cases (i), (iii) and (iv) we change the consumption share parameters (α_{it}^c) in Equation A31 (Appendix I):

$$C_{it} = \alpha_{it}^c VCC / PS_i \quad (1)$$

where C_{it} is real consumption, VCC is total value of consumption, and PS_i are supply prices of commodities. The alternative parameters, $\alpha_{it}^{c'}$, are chosen such that they always sum to 1:

$$\sum_i \alpha_{it}^{c'} = 1 = \sum_i \alpha_{it}^c \quad (2)$$

We considered a total of 75 different scenarios, each simulated for 20 years, giving a total of 1,560 annual solutions of the economy. Given the large number of simulations conducted, five main indicators are reported for each scenario: GDP, total CO₂ emissions, total energy use, energy rebound effect and carbon rebound effect. The first three indicators are provided by the model, within the equations shown in Appendix I.

We report GDP using the Laspeyres index to measure real GDP in the policy case compared to the base case GDP. Using the superscript B to denote base case values and superscript P (policy) for the scenarios, the comparable GDP is a weighted sum of the final demand elements (x_i) valued at base prices:

$$\frac{GDP_L^{Policy}}{GDP_L^B} = \frac{\sum_i P_i^B x_i^P}{\sum_i P_i^B x_i^B} \quad (3)$$

In the Laspeyres index, or other conventional indices such as the Fisher index, the base case price P_i^B reflects the social value of commodity i ; if p_i is high relative to p_j , and there is a reduction in the production of x_i and an increase of x_j in the policy cases, the formula reflects a reduction in real GDP.⁵

The energy calculations involve simple units where the energy rebound effect and the carbon rebound effect (RE) are calculated as a share of exajoules or tons potentially saved:

$$RE = \frac{\text{Potential energy (carbon) savings} - \text{Actual energy (carbon) savings}}{\text{Potential energy (carbon) savings}} \quad (4)$$

In equation 4, potential energy (or carbon) savings are the savings initially expected with each specific voluntary action using partial equilibrium analysis. If, for instance, a shock shifts 5% of base case spending on energy to other commodities, then a partial equilibrium calculation would expect energy use to be reduced by that 5%. Actual energy (carbon) savings is the economy-wide energy saved calculated at the new equilibrium by the model with the alternative parameter values compared to the base case. We should note that this is a domestic view of the rebound effects. Catalonia trades a large share of GDP, and changes in emissions in other countries which import from, and export to, Catalonia are not considered in this study. Below we detail the different scenarios tested, 6 scenarios under group 1 and 69 under group 2.

Table 3. Summary of the key features of scenarios.

Scenarios	Number of scenarios	Budget transferred year 1	Budget transferred year 20	Energy expenditures transferred year 1	Energy expenditures transferred year 20	Other details
1. Changes in Consumption Patterns (CCP) Scenarios	6	1.25%	25%			Six aggregate consumption groups: (1) primary sectors, (2) construction, (3) energy sectors, (4) manufacturing sectors, (5) services sectors and (6) transportation sectors.
2. Voluntary Energy Conservation	69					
2.1. Energy to Consumption and Savings Scenarios	3					Four energy commodities considered: (1) raw energy products, (2) coke and oil refining products, (3) electricity production and distribution services, and (4) manufactured gas and gaseous fuel distribution services.

⁵ This is the standard procedure to calculate the effect of a policy shock such as a carbon tax. In our counterfactuals we are shocking the parameters of the utility function, and thus there is no simple basis for welfare comparison with the base case parameters. We report this Laspeyres index since it reflects the official accounts of real GDP change should such a change in preferences occur.

2.1.1. E-C scenario— shift from energy to other commodities	1	1.25%	25%	We consider other (or non-energy) commodities the 60 non-energy commodities included in the SAM.
2.1.2. E-S scenario— shift from energy to savings	1	1.25%	25%	All energy conservation is allocated to savings.
2.1.3. E-CS scenario— shift from energy to other commodities and savings	1	1.25%	25%	There is a mix allocating monetary savings between non-energy commodities and savings.
2.2. <i>Energy to Individual Commodities Scenarios</i>	60	25%	25%	
2.3. <i>Individual Energy Commodities to Other Types of Energy Scenarios</i>	6	5%	5%	<i>We consider the three main energy products used in Catalan households: (1) coke and oil refining products (oil), (2) electricity production and distribution services (electricity) and (3) manufactured gas and gaseous fuel distribution services (gas)</i>

Changes in Consumption Patterns (CCP) Scenarios (group 1)

Usually, green consumption studies and public awareness campaigns provide information on the beneficial effects of moving within industries (e.g. food industry: from meat to vegetables). Given the macroeconomic perspective adopted in this study, we first assess the effects of shifting expenditures between broad consumption baskets. These scenarios may be partially associated with the households' intention of mitigating climate change, as there is no information on the effects of moving expenditures among specific groups of consumption.

We assume households exogenously change preferences and examine the impact on emissions. In order to simplify the analysis, we have set six consumption groups (indexed by g) by aggregating the 64 sectors: primary sectors (including agriculture), construction, energy sectors, manufacturing sectors (including food manufacturing), services sectors and transportation sectors.

Six scenarios have been run, one for each consumption group g . In each scenario g , a growing portion of household expenditures is transferred, each year, to group g from the rest of the consumption budget. We transfer, in year 1, 1.25% of the total budget towards consumption group g (representing a total of 1,403.48 million €), and this percentage grows linearly until it reaches a transfer of 25% in year 20 (representing a total of 28,069.62 million €), adding 1.25 percentage points each year. This way we can observe, dynamically, how a growing transfer addressed to the different aggregate consumption groups affects carbon emissions and GDP.

Voluntary Energy Conservation Scenarios (group 2)

This group of scenarios is more directly associated with what most would think of as household actions to reduce their carbon emissions compared to the previous group – using more efficient equipment, better house insulation or changing diets. Governments constantly appeal for energy conservation in order to achieve CO₂ emission reductions, and informed households carry them out intentionally to reduce their climate burdens. This group of simulations is aimed at testing the real potential of such voluntary actions, observing rebound effects, and examining how carbon taxes may be added to offset the rebound effects.

There are four energy commodities identified in the Catalan SAM: raw energy products (households spending a trivial 1.99 million € on coal), coke and oil refining products (3,561 million €), electricity production and distribution services (2,366 million €) and manufactured gas and gaseous fuel distribution services (540 million €). We consider two different subgroups of actions—switching to non-energy goods and switching to other energy goods.

A. Energy to Non-energy Consumption and Savings Scenarios

In the first case, households exogenously decide to conserve energy and reallocate spending to other commodities, or to savings. The exact reallocation is crucial in determining the effect they will have on the economy and carbon emissions. The higher savings result in higher investment spending.

Three different scenarios are assessed: (i) E-C scenario—shift from energy to other commodities: similar to CCP (group 1) scenarios just described, in year 1 1.25% of initial expenditures on energy (equalling 80.86 million € in 2014) is transferred to the other 60 commodities included in the Catalan SAM, in a way proportional to each sector's weight in the total household budget.⁶ The percentage reallocated grows at a rate of 1.25 points each year, until it reaches 25% of initial spending on energy in year 20 (equalling 1,617.15 million €). (ii) E-S scenario—shift from energy to savings: in year 1 1.25% of base case energy expenditures are transferred to household savings. This share grows linearly until it reaches 25% in year 20. (iii) E-CS scenario—shift from energy to other commodities and savings: this is a mix of the two previous scenarios, where in year one 1.25% of energy expenditures

⁶ See Freire-González (2011) for more detail on this re-spending proportional scenario.

are proportionally reallocated to both non-energy commodities and savings, depending on their weight in total household income. This share grows until it is 25% in year 20.

For each of these three energy reduction scenarios, we run an additional scenario in which a carbon tax completely offsets the carbon rebound effect, that is, we find a tax rate that makes $RE = 0$ in Equation 4. This uses the approach in Freire-González and Ho (2019), where the carbon tax per unit fuel j is:

$$t_j^c = t^x \theta_j \quad (5)$$

where t^x is the unit carbon tax in euros per ton of carbon and θ_j is the carbon emissions coefficient for energy type j . This tax is placed on all users of carbon, not just the household sector. Revenues obtained from the tax are used to increase government spending. A different carbon tax rate is needed for each year, depending on the CO_2 variation due to shifts in consumption.⁷

B. Energy to Individual Non-energy Commodities Scenarios

This second set of scenarios shows the specific impact of reallocating energy savings to each one of the individual commodities instead of all 60 non-energy goods at the same time as in set A above. A total of 60 simulations have been run, where, in each one and for each year, 25% of initial energy expenditures are transferred to one of the other 60 non-energy commodities included in the SAM.

C. Shifts between different types of Energy Commodities Scenarios

The third set of scenarios assesses a shift of household consumption from a specific source of energy to another. We consider the three main energy products used in Catalan households: coke and oil refining products (oil), electricity production and distribution services (electricity) and manufactured gas and gaseous fuel distribution services (gas). In each year of the simulations conducted, 5% of initial energy expenditures (or 323.33 million €) is transferred from one source of energy to another one. Six scenarios are analysed to

⁷ Equations (A21), (A32) and (A46) in Appendix I show how the carbon tax enters the economic system.

include all potential changes: (i) oil to gas, (ii) oil to electricity, (iii) gas to oil, (iv) gas to electricity, (v) electricity to oil and (vi) electricity to gas. Consider, for instance, two energy services: heating and transport. One could have households saving electricity (heating) but using more oil or gas (travelling); or saving gas (heating) but using more oil or electricity (travelling); or saving oil (heating) but using more electricity or gas (travelling).

3. Results and Discussion

This section describes the impact of the scenarios defined in Section 2.7. In each case we compare the alternative case variables with the base case values.

3.1. Changes in Consumption Patterns (CCP) Results

The CCP (group 1) scenarios are the reallocation of expenditures to each one of the six consumption groups from the other five groups. Figure 4 shows the effect on GDP over the 20-year horizon for each scenario g ; the line marked $g = \text{“Services”}$ denotes the scenario where expenditures are shifted to services. We observe how shifting consumption to services sectors initially lowers GDP but then raises it in the mid to long term. Higher GDP raises investment which raises future capital which contributes to further output expansion. Recall that we reallocate 25% of expenditures by year 20, which cumulates to a 2.9% increase in GDP. This GDP change is due to the rise in the relative price of services (relative to other commodities) over time in the base case; in this scenario the output of services expands, and thus the GDP index in Equation (3) rises relative to the base case consumption pattern. The relative price of services rises over time because they are more labour-intensive and benefit less from the accumulation of capital relative to the slow-growing labour supply. The other scenarios involving other sectors, like energy, primary and manufacturing, experience low or no GDP gain, along the transition path. Finally, shifting consumption towards transportation and construction sectors leads to lower GDP growth (-2.29% and -3.30% by year 20, respectively).

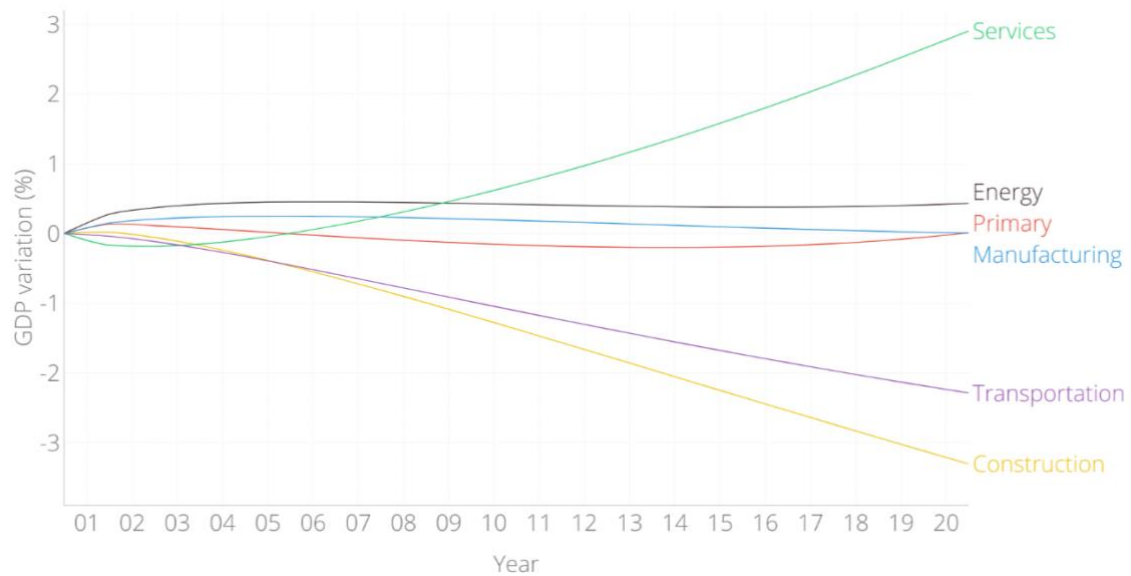


Fig. 4. GDP variation from increasingly directing household budget (1.25% year 1 to 25% year 20) to each of the six consumption groups, in relation to the base case.

Figure 5 plots the changes in carbon emissions for these scenarios. Redirecting household budgets to the energy group from other consumption leads to a 148.8% increase in CO₂ emissions in year 20, compared to the base case. The other scenario that raises economy-wide carbon emissions is directing expenditures to the transport group (16.42% increase in year 20). The other scenarios reduce global carbon emissions by year 20: -1.89% primary sectors, -3.17% manufacturing, -6.26% construction and -23.04% services.

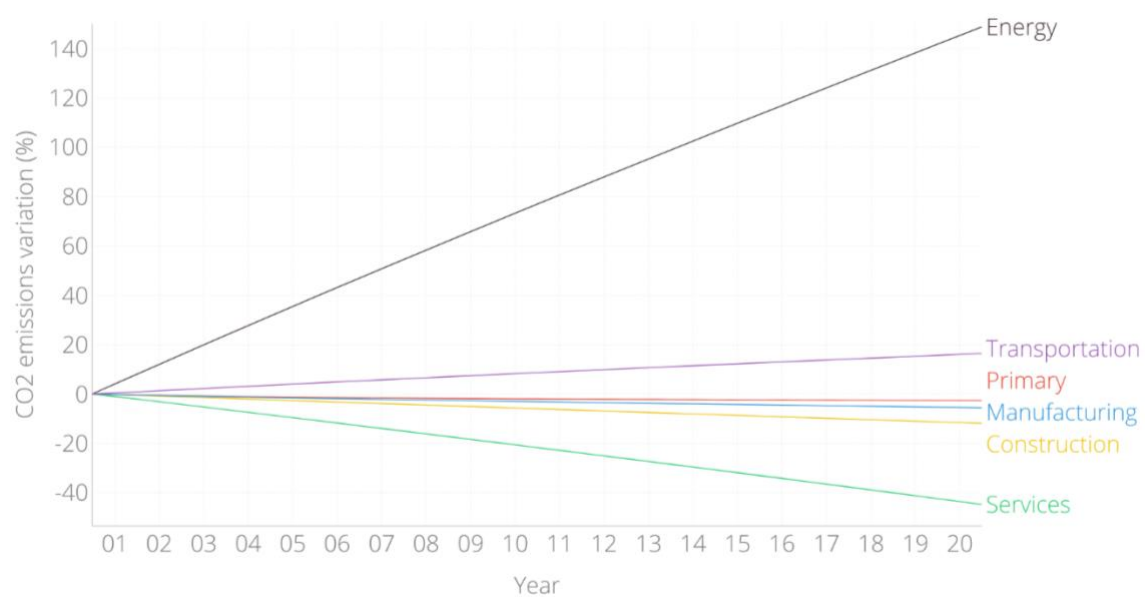


Fig. 5. Carbon emissions variation from increasingly directing household budget (1.25% year 1 to 25% year 20) to each of the six consumption groups, in relation to the base case.

There is only one consumption group which has clearly positive impacts on both GDP and climate change mitigation in the mid/long term: moving consumption patterns towards services sectors. Moving purchases towards other consumption groups would have limited or negative impacts for these indicators.

3.2. Voluntary Energy Conservation Results

Energy conservation measures such as using more efficient light bulbs are directly associated with carbon emission reductions. Households aiming to mitigate climate change may take them; however, they may not be as effective as expected due to rebound effects from re-spending. Furthermore, they may have a negative economic impact, as discussed next.

3.2.1. Shifting from Energy to Non-Energy Consumption and Savings

This section reports the impact of shifting a growing share of energy expenditures (1.25% in year 1 rising to 25% in year 20) to non-energy commodities (case E-C), to savings (E-S) or to both non-energy goods and savings (E-CS), as described in Section 2.7. Figure 6 shows the GDP variation for these three scenarios in relation to the base case. Transferring expenditures to households' savings (hence investment) leads to the highest GDP increase, 1.13% in year 20. On the other side, re-spending them on non-energy commodities leads to a trivial +0.07% change in year 20. A mix of new consumption and savings would lead to an increase of 0.28% in year 20.

Figure 6 also includes the economic impact of the scenarios where a carbon tax that offsets the carbon rebound effect is added to these 3 cases of shifts in energy consumption. That is, in the scenarios with the tax there is no carbon rebound when total economy-wide CO₂ is considered. The new tax revenues are used to raise government spending. Under such a taxation design, the only scenario that generates higher 20-year GDP than in the base case is the one that redirects energy expenditures to savings (E-S); note the GDP is reduced by the carbon tax, the E-S-Carbon tax path for GDP is lower than the E-S case. The reduction in GDP caused by the carbon tax is, however, not so large as to reverse the huge gain given by the shift to savings. In the other two cases, E-C and E-CS, the addition of a carbon tax also

leads to a fall in GDP, a fall that is large enough to overcome the small gain in E-CS so that GDP for the whole period is lower than the base case path (-0.17% for E-CS, and -0.25% for E-C, in year 20). The literature on carbon taxes shows how the negative GDP effects could be lower with an appropriate recycling of tax revenues instead of higher government spending as we have here (Freire-González and Ho, 2019).

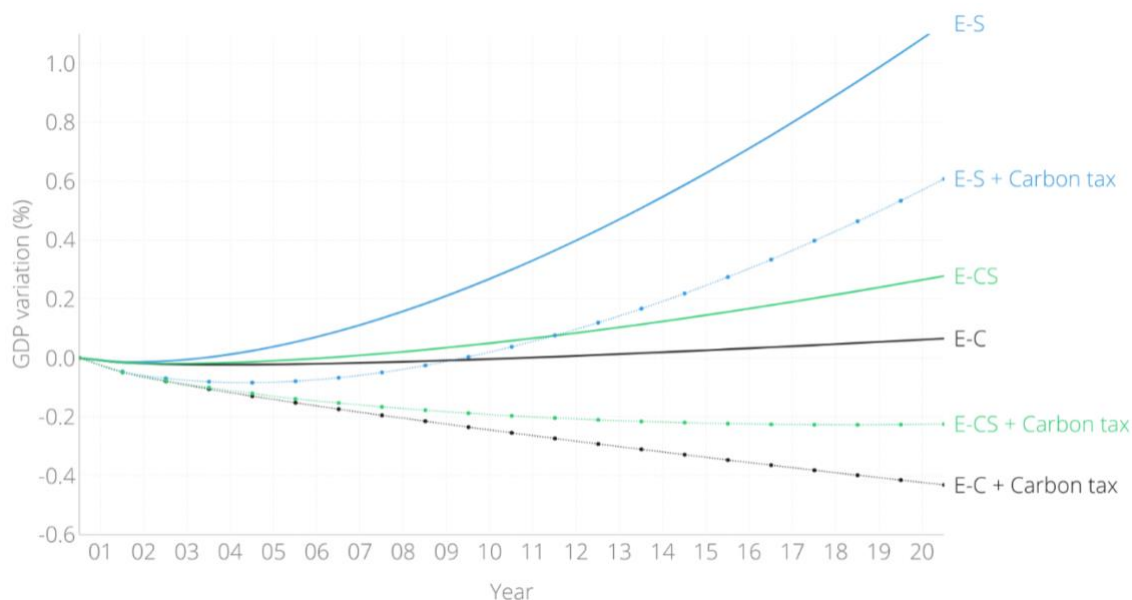


Fig. 6. GDP variation from redirecting energy expenditures (1.25% in year 1 to 25% in year 20) to other commodities or savings, in relation to the base case. E-S: energy to savings scenario; E-C: energy to commodities scenario; E-CS: energy to commodities and savings scenario.

Figure 7 shows the changes in carbon emissions in each scenario. All three of the consumption switches without a carbon tax experience a similar reduction. The energy to savings (E-S) case shows the smallest change, -4.39%, followed by E-CS with -4.72% and E-C with -4.80% (these are the changes averaged over the 20 years). The smallest reduction in emissions in the case where expenditures are reallocated to savings is due in part to its higher GDP path (top line in Figure 6) coming from higher investment, and due to the higher carbon intensity of investment goods (steel and cement). The different sources of energy have different carbon intensities and thus the energy rebound effects are slightly different; the average energy rebound effect for the period is 66.90% for E-S, 64.47% for E-C, and 64.95% for E-CS. Average carbon rebound effects values for the period are a bit lower than the energy rebounds, but similar: 65.68% for E-S, 63.32% for E-C, and 63.79% for E-CS.

In the cases where we add a carbon tax to the consumption shifts, we chose tax rates that exactly offsets the carbon rebound effects in each of the 3 cases. That is, we reduce carbon emissions by the potential reduction so that the expression in eq. 4 is zero. Since the three cases, E-C, E-S, E-CS all shift the same amount of spending out of the energy group, they all have the same potential reductions and the same targeted actual emissions, as reflected by the common line in Figure 7.

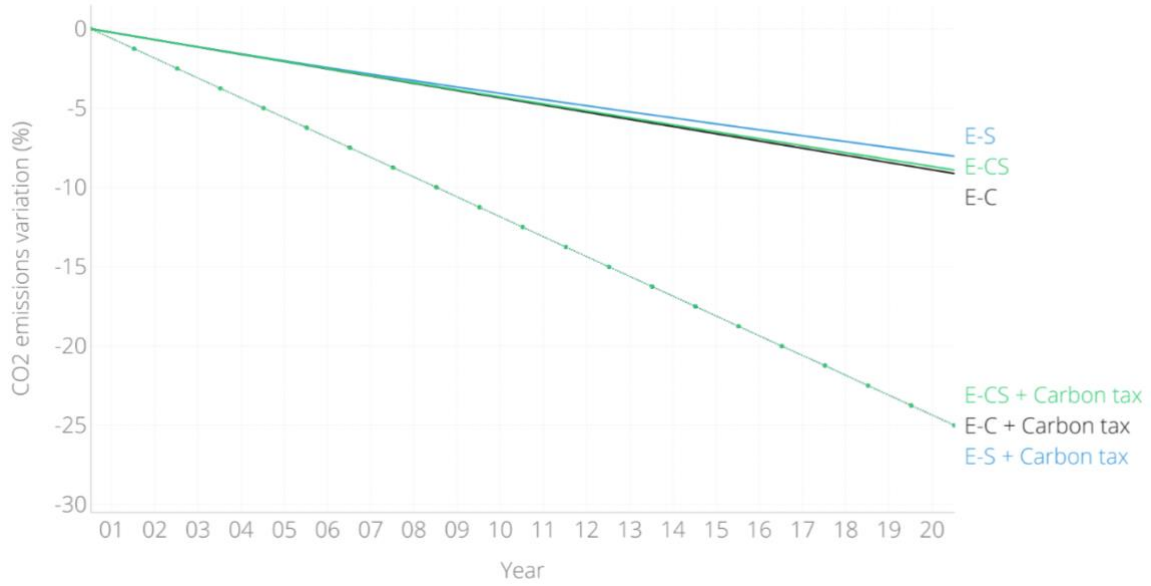


Fig. 7. CO₂ emissions variation from increasingly directing households' energy expenditures (1.25% year 1 to 25% year 20) to other commodities and/or savings, in relation to the base case. E-S: energy to savings scenario; E-C: energy to commodities scenario; E-CS: energy to commodities and savings scenario.

Figure 8 plots the carbon tax path needed in the 3 scenarios to avoid carbon rebound effects. They start in year 1 at 3.02 €/ton for the E-S scenario; 3.03 €/ton for the E-CS scenario; and 3.04 €/ton for the E-C scenario. In year 20 a carbon tax of 92.00 €/ton is needed for E-S; 86.80 €/ton for E-CS; and 85.70 €/ton for the E-C scenario. This means a carbon tax of between 2.4 and 3.6 €/ton per percentage point of voluntary energy reduction would offset carbon rebound effects over a 20-year period. Energy rebound effects are offset at the same time, with a slightly smaller offset given the different carbon intensities.

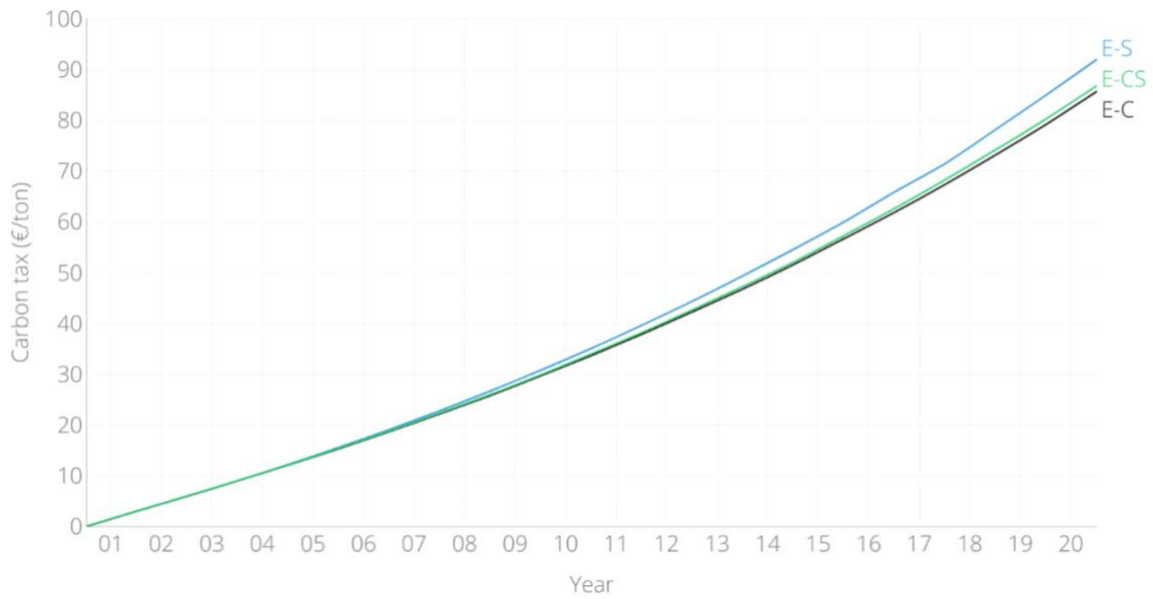


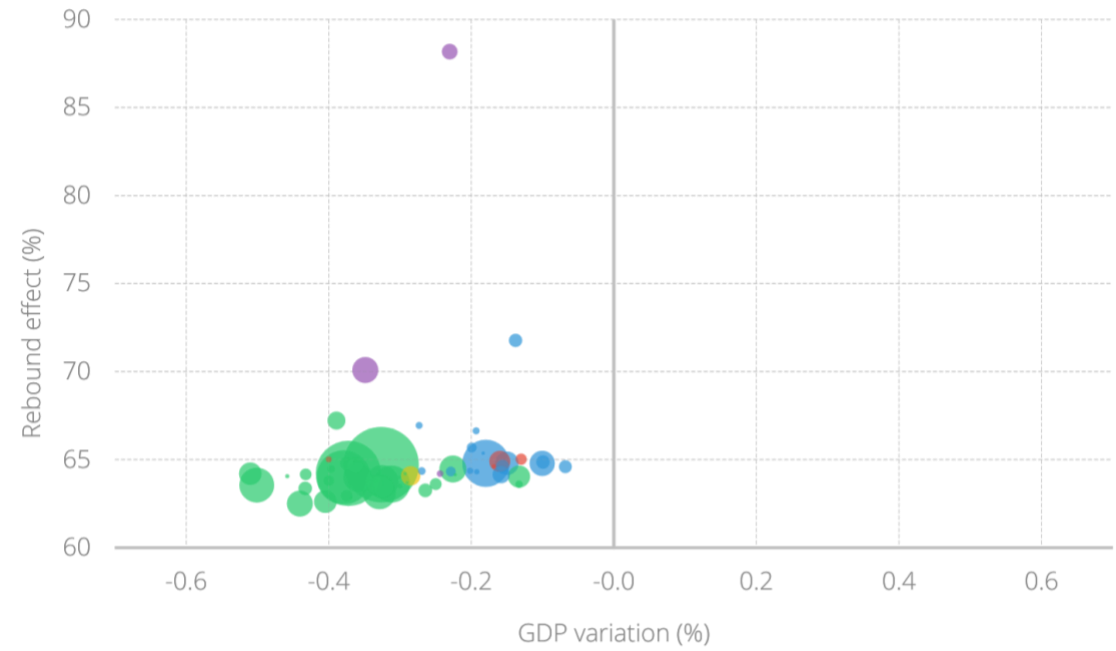
Fig. 8. Carbon tax that makes carbon rebound effect equal to zero, for each scenario, in each year of the simulation.

3.2.2. Shifting from Energy to Individual Non-energy Commodities Results

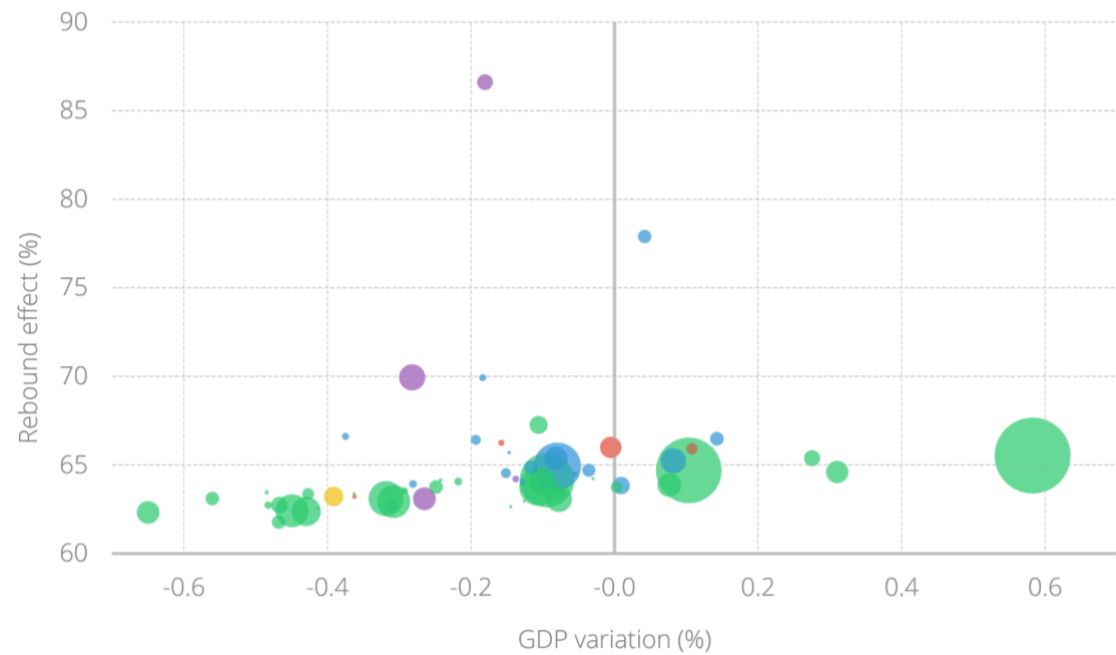
In order to provide full details of the potential re-spending effects of voluntary energy conservation measures, we reallocated spending to the 60 non-energy commodities one by one, as described in Section 2.7. In each simulation, 25% of total energy expenditures are redirected. In Table A2 in Appendix III, we report the GDP variation, the CO₂ emissions variation, and the energy rebound effect, in relation to the base case, for year 1 and for year 20, for each of the 60 scenarios. The bubble plot in Figure 9 summarizes the GDP variation and the energy rebound effect, for year 1 and year 20 of each simulation. The size of the 60 circles represents the level of consumer spending in the base year; the green colour is for services and the blue is for manufactured goods. The change in year 1 GDP is negative in all simulations; however, some of them become positive by the end of the period, particularly those related with services, as explained in the discussion of Figure 4 above. The GDP impact ranges from -0.07% (computers and electronic equipment) to -0.51% (sports, recreation and entertainment) in year 1, and from 0.58% (real estate activities) to -0.65% (sports, recreation and entertainment) in year 20. The effects are driven by the nature of the Laspeyres index for GDP, when we move spending towards goods with falling prices, GDP falls. On the other side, CO₂ emissions variations range from -9.80% (sale, maintenance and repair of motor vehicles) to -2.91% (air transport) for year 1, and from -9.81% (editing services) to -3.06% (air transport) in year 20. This is not surprising given the fuel use in the transportation

sector. The rebound effect is quite stable over time, ranging from 62.50% (sale, maintenance and repair of motor vehicles) to 88.17% (air transport) in year 1, and from 61.77% (editing services) to 86.61 (air transport) in year 20. In the case where spending is redirected to chemical products, the rebound effect is a remarkable 71.77% in year 1 and 77.90% in year 20.

Year 1



Year 20



● Primary
 ● Services
 ● Transport
 ● Construction
 ● Manufacturing
● Initial spending (€)

Fig. 9. GDP variation and energy rebound effect from re-spending 25% of all energy expenditures each year to each of the other 60 non-energy commodities. See detailed results in Appendix III.

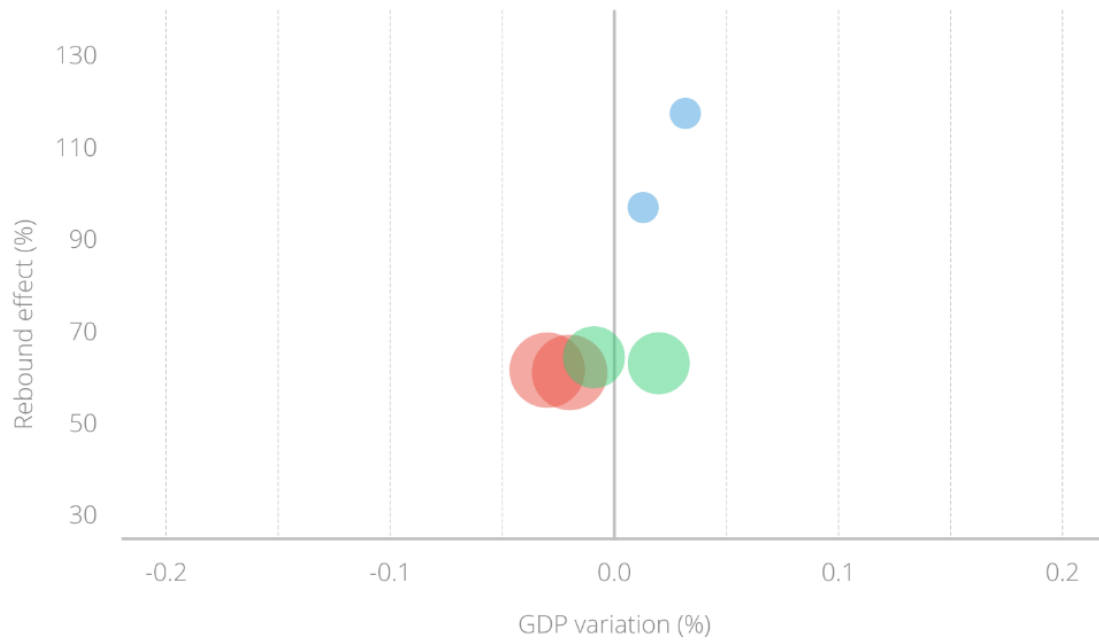
In any case, the strategy does not backfire (i.e., result in a rebound effect higher than 100%) when households carry out voluntary energy conservation actions and re-spend on other non-energy commodities. These scenarios always lead to energy and carbon reductions. However, they are not as effective as might be expected, with an average rebound effect of 64.85% in year 1 and 64.88% in year 20. As shown in previous scenarios, a carbon tax would help by supplementing these types of energy conservation actions or policies.

3.2.3. Individual Energy Commodities to Other Types of Energy Results

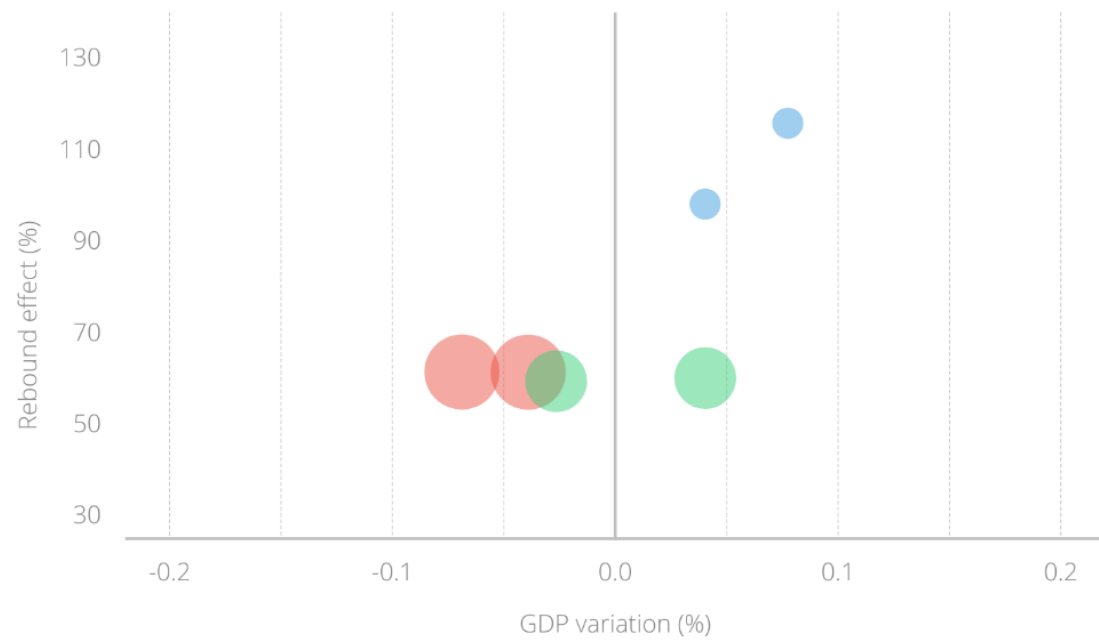
This group of scenarios transfers 5% of energy expenditures from a specific energy commodity to another one. The concept of energy rebound may not be so clear here since we are switching between types of energy, but we still wish to know the impact on total emissions when household switch fuels. Details of GDP variation, CO₂ emissions variation and energy rebound effect can be found in Table A3 of Appendix III. Figure 10 summarizes the results of the simulations in a bubble chart. We find two extreme cases, where there are no (or tiny) energy savings: reducing gas to increase oil (117.49% energy rebound effect in year 1 and 115.78% in year 20), and reducing gas to increase electricity (97.05% energy rebound effect in year 1 and 98.11% in year 20). The other shifts achieve energy rebounds between 59.41% and 64.49% (similar to most of the shifts to individual commodities discussed in Section 5.2.2).

However, if we focus on carbon emissions, there is a reduction of emissions in three cases (oil to gas, oil to electricity and gas to electricity) and an increase of emissions in the other three cases (electricity to oil, electricity to gas and gas to oil). The latter three cases backfire with carbon rebounds 126.98% for electricity to oil, 117.52% for electricity to gas and 109.44% for gas to oil in year 20. Although the other cases lead to carbon emission reductions, carbon rebounds are high (from 71.80% to 90.86% depending on the case). This makes these scenarios the least effective for climate change mitigation unless accompanied by different electricity generation methods or other policy measures.

Year 1



Year 20



- Oil reduction ● Gas reduction ● Electricity reduction
- Initial spending (€)

Fig. 10. GDP variation and energy rebound effect from re-spending monetary resources from energy conservation for each energy commodity (5% of all energy expenditures each year) to the other energy commodities included in the Catalan SAM, in relation to the base case. See detailed results in Appendix III.

3.2.4. Sensitivity analysis: AEEI and renewables share

Our modelling exercise, like other similar model simulations, is based on a set of assumptions about elasticities, productivity growth and technical change. The literature has included many examinations of the effects of alternative substitution elasticities, and we do not repeat this exercise here. We do examine the sensitivity of our results to alternative assumptions about technological change. The first test checks how different rates of *Autonomous Energy Efficiency Improvements* (AEEI) affect the simulated rebound effects. The second test checks how different projections of the renewable share in electricity generation affect the results, especially the carbon rebound effect.

While we have 75 different scenarios, we just need to choose one of them to illustrate the sensitivity of the model under the specified changes: scenario in section 3.2.1. “Shifting from Energy to Non-Energy Consumption”. As this scenario includes energy savings, it is likely more affected by these alternative projections than other scenarios.

To examine the impact of more optimistic changes in technology, we introduced a 1% yearly improvement AEEI in both the base case and the policy case. In section 3.2.1, in the E-C scenario, the energy rebound was 64.48% in year 20, and the carbon rebound was 63.50%. When we use the higher AEEI rate, the energy rebound due to consumption switching is 64.50% and the carbon rebound was 63.53%; that is, the differences in rebounds between the original AEEI assumption and the higher one are only 0.04% and 0.05% in year 20. For year 1 the differences are also a trivial 0.07% and 0.09%. The AEEI assumptions does not importantly affect the results for two reasons: (1) we estimate rebounds not from technological change but from voluntary consumer actions (conservation), (2) since we compare a base case with a scenario case, the percentage change is similar with alternative considerations of technological change. This is because both base and policy simulations include the same AEEI rates in each period.

For alternative projections of renewables, we run a scenario in which we assume that the renewables share is doubled in all years of the projection period. In the original projection with the renewable share rising at historical trends, the energy rebound is 64.70% in year 1 and the carbon rebound is 63.11%. In the higher renewable alternative, the energy rebound is 65.96% in year 1 and carbon rebound is 63.11%, that is, the energy rebound differs by

1.95% and the carbon rebound is unchanged compared to the original renewal projection. Differences in year 20 are similar. These small differences show that the renewable assumptions play only a minor role in the horizon of our analysis. This, of course, does not mean that much higher renewables in the future is not important in the rebound calculations, it will be important. However, for plausible increases in the next 20 years, the impact is minor. We note again that we have actual data on renewables penetration for the first years of the simulation and used it to estimate a regression to project for the next 20 years.

4. Conclusions

Voluntary conservation measures aimed at households and promoted by governments are currently used to mitigate climate change, as they are perceived to be inexpensive and effective. However, they may not be as effective as thought by policymakers and public opinion. The effectiveness of voluntary measures in reducing carbon emissions depends largely on how households behave.

Different potential scenarios of household consumption adjustment are comprehensively assessed here in order to show their effectiveness in mitigation, and the impact on economic growth over time. We make several contributions here. First, general changes in consumption patterns are not usually associated with voluntary energy conservation due to the lack of information by households and governments. Many studies discuss the potential effects of green consumption (shifting consumption within a specific sector, rather than between sectors), but not moving consumption between larger categories as done in this study. Our consideration of wider consumption categories here allows a broader public awareness and perhaps the consideration of industrial or other macroeconomic policies. We find that moving household budgets towards energy or transport sectors would increase carbon emissions, while moving them towards primary goods, manufacturing, construction or services would reduce them. The best case for climate change and the economy (GDP) is to move consumption towards services activities.

Secondly, we examine more narrowly targeted voluntary energy conservation measures. Moving energy expenditures towards non-energy consumption commodities or savings (starting from current consumption and savings patterns) reduces both energy use and

carbon emissions. However, the energy and carbon rebound effects are quite high, ranging from 64.5% to 66.9% for the energy rebound effect, and 63.3% to 65.7% for the carbon rebound effect. We show how a carbon tax of between 2.4 and 3.6 €/ton per percentage point of voluntary energy reduction could offset rebound effects. The carbon taxes reduce GDP, but the negative effect is modest relative to the reduction in emissions. Thirdly, we examine the re-spending effects for a large range of specific commodities and estimate a range of energy rebound effects from 61.77% to 117.49%. The highest rebounds are for moving from one specific energy source to another: natural gas being substituted for oil gives an energy rebound of 117.5%, and substituting gas by electricity 98.1%; electricity being substituted for oil has a carbon rebound of 128.1%, electricity substituting for natural gas, 118.9%, and gas being substituted for oil, 109.4%. The GDP effects are varied for such a large range of commodities, depending on whether the receiving sector is enjoying a rise in relative prices over time.

These results show how energy savings are re-spent is an important issue to be considered by policymakers, and an aspect to be included in assessments and policy design. If, for instance, households conserve energy but use the saved money to buy flights for vacations, there will be little net carbon emission reduction (rebound effect between 86.61% and 88.17%), so the effect of this policy would become very limited. There are even extreme cases when they backfire, for example, when a specific energy source is substituted for another one.

This is the first study of its kind using this type of growth model. Our results show higher rebound effects than previous studies (most of them using input–output analysis and extensions), as shown in Sorrell et al. (2020). It needs to be replicated for other regions, including different specifications, and providing comparisons, either within the same modelling framework or using other frameworks and methodologies. Future analyses should take more careful account of possible paths of low-carbon electricity generation instead of our simple assumption here. Beyond the traditional limitations of CGE modelling, a current limitation of this study is the industry/commodity disaggregation of the SAM we have developed. Higher detail could lead to higher rebounds for specific commodities and lower rebounds for other ones, within the same group. However, in any case, some specific actions would backfire.

One important conclusion is that voluntary (or promoted) energy conservation measures in households, in most cases, lead to a reduction in both energy use and carbon emissions, but these reductions are not as high as expected. While we do not have a specific policy recommendation, we can say that while voluntary energy conservation measures are important for many reasons (not just economic), additional measures need to be implemented to be relevant for effective climate change mitigation. The design of comprehensive complex policies that include several measures (i.e., foster voluntary energy conservation, plus re-spending measures, plus carbon taxes, etc.), is necessary. Such a more comprehensive and nuanced approach could supplant the simple assumption that appealing to households' public spirit is an inexpensive and efficient means to fight climate change.

Acknowledgements

This project received the support of the Beatriu de Pinós postdoctoral program of the Government of Catalonia's Secretariat for Universities and Research of the Ministry of Business and Knowledge. It is also supported by a grant from the Harvard Global Institute.

Data Availability Statement

The results of specific variables for the different scenarios resulting from this study are available from the corresponding author, upon reasonable request.

References

- Alfredsson, E. C. (2004) "Green" consumption—no solution for climate change. *Energy* 29(4), 513–524.
- Armington, P.S. (1969) A theory of demand for products distinguished by place of production. *Staff Papers—International Monetary Fund* 16(1), 159–178.
- Aspalter, L. (2016) Estimating industry-level Armington elasticities for EMU countries. Working Paper No. 217. Department of Economics, Vienna University of Economics and Business (WU).

- Babatunde, K. A., Begum, R. A., Said, F. F. (2017). Application of computable general equilibrium (CGE) to climate change mitigation policy: A systematic review. *Renewable and Sustainable Energy Reviews*, 78, 61-71.
- Beckman, J., Hertel, T., Tyner, W. (2011). Validating energy-oriented CGE models. *Energy Economics*, 33(5), 799-806.
- Bjelle, E. L., Steen-Olsen, K., Wood, R. (2018) Climate change mitigation potential of Norwegian households and the rebound effect. *Journal of Cleaner Production* 172, 208–217.
- Böhringer, Christoph, Thomas F. Rutherford, Edward J. Balistreri, and John Weyant, 2012. “Introduction to the EMF 29 Special Issue on the Role of Border Carbon Adjustment in Unilateral Climate Policy (EMF 29).” *Energy Economics* 34, S95–S96.
- Cao, J., Ho, M. (2017) Appendix A. Economic-Environmental Model of China (version 18), Harvard-China Project Working Paper.
- <https://chinaproject.harvard.edu/files/chinaproject/files/chinaces-hhmodel.2018.pdf>.
- Cao, J., Ho, M. S., Jorgenson, D. W., Nielsen, C. P. (2019) China’s emissions trading system and an ETS-carbon tax hybrid. *Energy Economics* 81, 741–753.
- Druckman, A., Chitnis, M., Sorrell, S., Jackson, T. (2011) Missing carbon reductions? Exploring rebound and backfire effects in UK households. *Energy Policy* 39(6), 3572–3581.
- Font Vivanco, D., Kemp, R., van der Voet, E. (2016b) How to deal with the rebound effect? A policy-oriented approach. *Energy Policy* 94, 114–125.
- Font Vivanco, D., McDowall, W., Freire-González, J., Kemp, R., van der Voet, E. (2016a) The foundations of the environmental rebound effect and its contribution towards a general framework. *Ecological Economics* 125, 60–69.
- Freire-González, J. (2011) Methods to empirically estimate direct and indirect rebound effect of energy-saving technological changes in households. *Ecological Modelling* 223(1), 32–40.
- Freire-González, J. (2020) Energy taxation policies can counteract the rebound effect: Analysis within a general equilibrium framework. *Energy Efficiency* 13(1), 69–78.
- Freire-González, J., Ho, M. S. (2018) Environmental fiscal reform and the double dividend: Evidence from a dynamic general equilibrium model. *Sustainability* 10(2), 501.
- Freire-González, J., Ho, M. S. (2019) Carbon taxes and the double dividend hypothesis in a recursive-dynamic CGE model for Spain. *Economic Systems Research* 31(2), 267–284.

- Freire-González, J., Puig-Ventosa, I. (2015) Energy efficiency policies and the Jevons paradox. *International Journal of Energy Economics and Policy* 5(1), 69.
- Hertel, T., McDougall, R., Narayanan, B., Aguiar, A. (2014) GTAP 8 data base documentation. Chapter 14: Behavioral parameters. https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=4551.
- Imbs, J., Mejean, I. (2010) Trade elasticities: A final report for the European Commission (No. 432). Directorate General Economic and Financial Affairs (DG ECFIN), European Commission.
- Jorgenson, D., Goettle, R., Ho, M.S., Wilcoxon, P. (2013) *Double Dividend: Environmental Taxes and Fiscal Reform in the United States*. MIT Press, Cambridge, MA.
- Jorgenson, D., Goettle, R., Ho, M., Wilcoxon, P. (2018) The welfare consequences of taxing carbon. *Climate Change Economics* (9)1, 1840013.
- Klump, R., McAdam, P., Willman, A. (2011) The normalized CES production function: Theory and empirics. European Central Bank, Working Paper 1294.
- Mas Ivars, M., Serrano Martínez, L., Pérez García, F., Uriel Jiménez, E. (2018) Ciclo económico, acumulación de capital en España y crecimiento regional (en el siglo XXI). Documentos de trabajo. Fundación BBVA (1), 1.
- Murray, C.K. (2011) Income dependent direct and indirect rebound effects from ‘green’ consumption choices in Australia. Munich Personal RPEC archive, MPRA Paper No. 34973.
- Murray, C. K. (2013) What if consumers decided to all “go green”? Environmental rebound effects from consumption decisions. *Energy Policy* 54, 240–256.
- Németh, G., Szabó, L., Ciscar, J. C. (2011) Estimation of Armington elasticities in a CGE economy–energy–environment model for Europe. *Economic Modelling* 28(4), 1993–1999.
- Ross, M. T. (2007) Documentation of the applied dynamic analysis of the global economy (ADAGE) model. RTI Work Paper (05-01).
- Rutherford, T. (2003) Lecture notes on constant elasticity functions. Mimeo, University of Colorado.
- Saunders, H. D. (1992) The Khazzoom-Brookes postulate & neoclassical growth. *The Energy Journal* 13(4), 131–148.
- Sorrell, S. (2007) The rebound effect: An assessment of the evidence for economy-wide energy savings from improved energy efficiency. UK Energy Research Centre.

Sorrell, S., Gatersleben, B., Druckman, A. (2020) The limits of energy sufficiency: A review of the evidence for rebound effects and negative spillovers from behavioural change. *Energy Research & Social Science* 64, 101439.

van den Bergh, J. C. (2011) Energy conservation more effective with rebound policy. *Environmental and Resource Economics* 48(1), 43–58.

van den Bergh, J. C. (2015) Pricing would limit carbon rebound. *Nature* 526(7572), 195–195.

Appendix I. Description of the recursive-dynamic economy–energy–environment CGE model for Catalonia.

In this appendix we include a detailed description of the model used in this research, including the behavioural equations. The model described is partly based on Jorgenson et al. (2013), Freire-González and Ho (2019) and the technical report of Cao and Ho (2017), with some modifications.

A1. Production

We identify 64 different production activities producing 64 different commodities. Production is carried out using capital, labour, land and inputs (including energy and non-energy inputs). Profits in each industry j are maximized (A1), subject to a production restriction (A2):

$$profit_j = PI_j QI_j - P_j^{KD} KD_j - PL_j LD_j - PT_j TD_j - \sum_i PB_{ij} A_{ij} \quad (A1)$$

$$QI_j = f(KD_j, LD_j, TD_j, A_{1j}, \dots, A_{nj}, t) \quad (A2)$$

where PI_j and QI_j are the price and quantity of output of industry j ; P_j^{KD} and KD_j are the price and quantity of capital; PL_j and LD_j are the price and quantity of labour; PT_j and TD_j are the price and quantity of land and PB_{ij} and A_{ij} are the price and quantity of intermediate input i to industry j .

The production structure of the model is expressed in prices using cost dual functions, instead of quantity primary production functions. This kind of structure represents the output price as a function of input prices and technology. A nested series of constant elasticity of substitution (CES) functions is used in this version of the model. Figure 2 shows the nesting structure of production followed by the economic model.

At the top tier of the nested structure, output QI is produced by combining the value-added-energy composite (VE) with the non-energy composite (M), using CES production functions. The value equation and the cost function are:

$$PI_{jt} QI_{jt} = P_{jt}^{VE} VE_{jt} + PM_{jt} M_{jt} \quad (A3)$$

$$PI_{jt} = \frac{k_{jt}^{QI}}{g_{it}} \left[\alpha_{M_{jt}}^{\sigma_{jt}^{QI}} PM_{jt}^{(1-\sigma_{jt}^{QI})} + (1 - \alpha_{M_{jt}})^{\sigma_{jt}^{QI}} P_{jt}^{VE(1-\sigma_{jt}^{QI})} \right]^{\frac{1}{1-\sigma_{jt}^{QI}}} \quad (A4)$$

where k_{jt}^{QI} is the parameter of the function set at the calibration process; g_{it} represents total factor productivity (TFP) of industry i at period t ; $\alpha_{M_{jt}}$ is the share for all material inputs into industry i at period t ; and $1/\sigma_{jt}^{QI}$ is the elasticity of substitution between the two inputs.

Input demands from the cost function are:

$$VE_{jt} = \left(\frac{k_{jt}^{QI}}{g_{jt}} \right)^{1-\sigma_{jt}^{QI}} \left[(1 - \alpha_{M_{jt}}) \frac{PI_{jt}}{P_{jt}^{VE}} \right]^{\sigma_{jt}^{QI}} QI_{jt} \quad (A5)$$

$$M_{jt} = \left(\frac{k_{jt}^{QI}}{g_{jt}} \right)^{1-\sigma_{jt}^{QI}} \left[\alpha_{M_{jt}} \frac{PI_{jt}}{PM_{jt}} \right]^{\sigma_{jt}^{QI}} QI_{jt} \quad (A6)$$

The weights of these functions (α_{jt} and k_{jt}) are obtained from a calibration process, using the base case data.⁸ The value and cost equations for the primary factor–energy (KLT)E composite and the value-added (VA) composite are:

$$P_{jt}^{VE} VE_{jt} = P_{jt}^{VA} VA_{jt} + P_{jt} E_{jt} \quad (A7)$$

$$P_{jt}^{VA} VA_{jt} = P_{jt}^{KD} KD_{jt} + P_{jt} L_{jt} LD_{jt} + P_{jt} T_{jt} TD_{jt} \quad (A8)$$

$$P_{jt}^{VE} = \frac{1}{k_{jt}^{VE}} \left[\alpha_{E_{jt}}^{\sigma_{jt}^{VE}} P_{jt}^{VE(1-\sigma_{jt}^{VE})} + (1 - \alpha_{E_{jt}})^{\sigma_{jt}^{VE}} P_{jt}^{VA(1-\sigma_{jt}^{VE})} \right]^{\frac{1}{1-\sigma_{jt}^{VE}}} \quad (A9)$$

$$P_{jt}^{VA} = \frac{1}{k_{jt}^{VA}} \left[\alpha_{K_{jt}}^{\sigma_{jt}^{VA}} P_{jt}^{KD(1-\sigma_{jt}^{VA})} + \alpha_{L_{jt}}^{\sigma_{jt}^{VA}} P_{jt}^{L(1-\sigma_{jt}^{VA})} + (1 - \alpha_{K_{jt}} - \alpha_{L_{jt}})^{\sigma_{jt}^{VA}} P_{jt}^{T(1-\sigma_{jt}^{VA})} \right]^{\frac{1}{1-\sigma_{jt}^{VA}}} \quad (A10)$$

The input demands from these cost functions are:

$$E_{jt} = \left(\frac{1}{k_{jt}^{VE}} \right)^{1-\sigma_{jt}^{VE}} \left[\alpha_{E_{jt}} \frac{P_{jt}^{VE}}{P_{jt}^{VE}} \right]^{\sigma_{jt}^{VE}} VE_{jt} \quad (A11)$$

$$VA_{jt} = \left(\frac{1}{k_{jt}^{VA}} \right)^{1-\sigma_{jt}^{VA}} \left[(1 - \alpha_{E_{jt}}) \frac{P_{jt}^{VE}}{P_{jt}^{VA}} \right]^{\sigma_{jt}^{VA}} VE_{jt} \quad (A12)$$

$$KD_{jt} = \left(\frac{1}{k_{jt}^{VA}} \right)^{1-\sigma_{jt}^{VA}} \left[\alpha_{K_{jt}} \frac{P_{jt}^{VA}}{P_{jt}^{KD}} \right]^{\sigma_{jt}^{VA}} VA_{jt} \quad (A13)$$

⁸ See Rutherford (2003) and Klump et al. (2011) for more detail.

$$LD_{jt} = \left(\frac{1}{k_{jt}^{VA}}\right)^{1-\sigma_{jt}^{VA}} \left[\alpha_{L_{jt}} \frac{p_{jt}^{VA}}{p_{L_{jt}}} \right]^{\sigma_{jt}^{VA}} VA_{jt} \quad (A14)$$

$$TD_{jt} = \left(\frac{1}{k_{jt}^{VA}}\right)^{1-\sigma_{jt}^{VA}} \left[(1 - \alpha_{K_{jt}} - \alpha_{L_{jt}}) \frac{p_{jt}^{VA}}{p_{T_{jt}}} \right]^{\sigma_{jt}^{VA}} VA_{jt} \quad (A15)$$

At the lower tiers of the nesting structure, the energy and materials (non-energy inputs: NE) composites are defined through two different kinds of production functions. Energy industries (IE) in this model are the extraction of energy products (*EnEx*), coke and petroleum refining products (*Coke*), production and distribution of electricity (*EnEle*) and production and distribution of natural gas (*Prodgas*). They are modelled using CES production functions:

$$PE_{jt}E_{jt} = \sum_{k \in IE} PB_{kjt} A_{kjt} \quad (A16)$$

$$PE_{jt} = \frac{1}{k_{jt}^E} \left[\sum_{k \in IE} \alpha_{kjt}^E \sigma_{jt}^E PB_{kjt}^{(1-\sigma_{jt}^E)} \right]^{\frac{1}{1-\sigma_{jt}^E}} \quad IE = \{EnEx, Coke, EnEle, Prodgas\} \quad (A17)$$

$$A_{kjt} = \left(\frac{1}{k_{jt}^E}\right)^{1-\sigma_{jt}^E} \left[\alpha_{kjt}^E \frac{PE_{jt}}{PB_{kjt}}\right]^{\sigma_{jt}^E} E_{jt} \quad k \in IE \quad (A18)$$

Material composites are modelled using Cobb-Douglas production functions:

$$PM_{jt}M_{jt} = \sum_{k \in NE} PS_{kt} A_{kjt} \quad NE = \{Agri, \dots, Otherservices\} \quad (A19)$$

$$PM_{jt} = \sum_{k \in NE} PS_{kt}^{\alpha_{kjt}^M} \quad (A20)$$

Taxes on outputs and inputs are included. Amongst them, there are *ad valorem* or unitary “resource taxes” levied on extraction industries, and set separately with rate (t_j^{res}). Another option is to set *ad valorem* externality taxes (t_j^x) or unitary ones (t_j^c). These are implemented/modified in order to tax energy, other resources or emissions, etc. They modify the output prices of these industries:

$$PI_j^t = (1 - t_j^s + t_j^t + t_j^{sp} + t_j^o + t_j^{res} + t_j^x + t_j^c) PO_j + t_j^c \quad (A21)$$

where t_j^s are subsidies to production, t_j^t are sales taxes, t_j^{sp} are special taxes (which includes special taxes on alcohol, tobacco, hydrocarbons, electricity and retail hydrocarbons) and t_j^o are other taxes. Supply and use tables are used in this model, which distinguishes industries from commodities. The relations between commodities and industries are:

$$VQC_i = PC_i QC_i = \sum_j m_{ji}^r PI_j^t QI_j \quad (A22)$$

$$PC_i = \sum_j PI_j^t m_{ji}^c \quad (A23)$$

$$m_{ji}^r = \frac{M_{ji}}{\sum_k M_{jk}} \quad (A24)$$

$$m_{ji}^c = \frac{M_{ji}}{\sum_k M_{ki}} \quad (A25)$$

where VQC_i is the value of domestic commodity i ; PC_i is the price of this domestic commodity; QC_i is the quantity; m_{ji}^r and m_{ji}^c are the row and column shares of use and supply tables that transform industries into commodities.

A2. Households

For households we have established different economic roles. These are the most important ones represented in this model: consumption of commodities, supply of labour, ownership of part of capital stock and exchange of transfers with government and the foreign sector. Aggregate private income (Y^p) can be written as:

$$Y^p = YL + DIV + G_I + G_{transfer} + R_{transfer} - FEE \quad (A26)$$

where YL is aggregate labour income, DIV is dividend income, G_I is interest received from public debt, $G_{transfer}$ is income transfers from the government, $R_{transfer}$ is income from the rest of the world and FEE are non-tax fees. Aggregate labour income is gross labour compensation paid by employers less taxes:

$$YL_t = (1 - t^{ss} - t^L) PL_t LS_t \quad (A27)$$

where t^{ss} is the aggregate social security tax rate on labour, t^L is labour tax rate, PL are wages and LS is aggregate supply of labour. These incomes are allocated between the total value of consumption (VCC_t) and savings (S_t^p), using a savings rate (s_t):

$$S_t^p = s_t Y_t^p = Y_t^p - VCC_t \quad (A28)$$

Households' utility (U_t) comes from the consumption of commodities (C_{it}). Total consumption expenditures are allocated using a Cobb-Douglas formulation, using consumption shares (α_{it}^c) from the SAM:

$$U_t = \sum_i \alpha_{it}^c \log C_{it} \quad (A29)$$

$$VCC = \sum_i PS_i C_i \quad (A30)$$

$$C_{it} = \alpha_{it}^c VCC / PS_i \quad (A31)$$

where PS_i are supply prices of commodities (Equation A57).

A3. Government

Government has different roles in the model, but obtaining revenue from the private sectors and redistributing them is its main role. Total government revenues (Rev) are:

$$Rev = R_K + R_L + R_{Prop} + R_{YK} + R_{VAT} + R_{Sales} + R_{Special} + R_O + R_{SS} + R_{Tariff} + TAXN_{HH} + TAXN_{ENT} - R_{subsidy} + R_c \quad (A32)$$

where R_K are direct taxes on capital; R_L are taxes on labour; R_{Prop} are taxes on property; R_{YK} are taxes on dividends; R_{VAT} are indirect taxes on production and commodities; R_{Sales} are taxes on sales; $R_{Special}$ are special taxes on alcohol, tobacco, hydrocarbons, electricity and retail hydrocarbons; R_O are other taxes; R_{SS} are social security contributions; R_{Tariff} are tariffs; $TAXN_{HH}$ are other non-tax revenues from households; $TAXN_{ENT}$ are other non-tax revenues from firms; $R_{subsidy}$ are production subsidies and R_c are revenues from a tax on CO₂ emissions. These revenues are given by:

$$R_K = \sum_j t^k \left((1 - t_j^{vat}) PK_j KD_j - \sum_j t^p PK_j KD_j \right) \quad (A33)$$

$$R_L = t^l \sum_j PL_j LD_j \quad (A34)$$

$$R_{Prop} = t^p \sum_j PK_j KD_j \quad (A35)$$

$$R_{YK} = t^{yk} DIV_{gross} \quad (A36)$$

$$R_{VAT} = \sum_j t_j^{vat} \left(PK_j KD_j + PL_j LD_j + P_{Land_j} L_{Land_j} \right) \quad (A37)$$

$$R_{Sales} = \sum_j t_j^t PO_j QI_j \quad (A38)$$

$$R_{Special} = \sum_j t_j^{sp} PO_j QI_j \quad (A39)$$

$$R_O = \sum_j t_j^o PO_j QI_j \quad (A40)$$

$$R_{SS} = t^{ss} \sum_j PL_j LD_j \quad (A41)$$

$$R_{Tariff} = \sum_i t_i^m e PM_i M_i \quad (A42)$$

$$TAXN_{HH} = g_{NHH} GDP \quad (A43)$$

$$TAXN_{ENT} = G_{ENT} GDP \quad (A44)$$

$$R_{subsidy} = \sum_j t_j^s PO_j QI_j \quad (A45)$$

$$R_c = \sum_j (t_j^v PO_j QI_j + t_j^c QI_j + t_j^{mv} e PM_j M_j + t_j^{mc} M_j) \quad (A46)$$

In these equations, t_j^{vat} is the VAT tax rate, e the exchange rate, t_i^m the imports tax rate, t_i^{mv} the *ad valorem* carbon tax on imports, t_j^{mc} the unit carbon tax on imports, g_{NHH} the coefficient for non-tax payments by households to the government, G_{ENT} the coefficient for non-tax payments by enterprises to government and GDP the gross domestic product.

Government expenditure is modelled by the sum of the value of purchases of commodities by the government (VGG), government investments (G_{INV}), government transfers to the rest of the world (G_{IR}), social contributions to households (G_{SS}), interest paid for public debt (G_{INT}) and other transfers to households (G_{Transf}).

$$Expend = VGG + G_{INV} + G_{IR} + G_{SS} + G_{INT} + G_{Transf} \quad (A47)$$

$$VGG = GG PGG \quad (A48)$$

$$G_{Transf} = \gamma^{tr} PL_t POP_t \quad (A49)$$

GG is the aggregate real government purchases, and PGG is its price, γ^{tr} is the parameter for transfers, obtained from the SAM, PL_t is wage rate and POP_t is population. Government purchase patterns are set using current individual shares (α_i^G) from total government purchases, taken from the SAM:

$$PS_i G_i = \alpha_i^G VGG \quad (A50)$$

Government deficit (ΔG_t), which is determined exogenously, is expenditures ($Expend_t$) less revenues (Rev_t):

$$\Delta G_t = Expend_t - Rev_t \quad (A51)$$

A.4. Capital

Sectoral capital stock (K_{jt}) is determined in each period as the stock of the previous year (K_{jt-1}), applying to it a depreciation rate (δ), plus current investments (I_{jt}). Capital is allocated to individual sectors based on sectoral rates of return. The supply of capital stock is a function of all of the market capital rental prices:

$$K_{jt} = (1 - \delta)K_{jt-1} + I_{jt} \quad (A52)$$

$$K_{jt} = K_j(PK_1, \dots, PK_n) \quad (A53)$$

Profits of firms are allocated to corporate income taxes (R_K), retained earnings (RE_j) and dividends (DIV):

$$\sum_j Profits_j + \sum_j PK_j KD_j + \sum_j PT_j TD_j = R_K + RE_j + DIV \quad (A54)$$

In each period, fixed industry shares from the SAM (α_{jt}^I) applied to total investment (II_t) determines the sectoral value of investments ($PI_{jt}I_{jt}$):

$$PI_{jt}I_{jt} = \alpha_{jt}^I II_t \quad (A55)$$

A.5. Foreign sector

The foreign sector mainly imports and exports commodities and provides and receives transfers. As this is a single-country model, the total domestic supply (DS_i) is modelled following an Armington CES function between the domestically produced commodities (DC_i) and imported ones (M_i).

$$DS_i = A_0 [\alpha^d DC_i^\rho + \alpha^m M_i^\rho]^{1/\rho} \quad (A56)$$

where α^d and α^m are the shares of domestic and imported commodities, taken from the SAM, and the elasticity of substitution is $\sigma = 1/(1 - \rho)$. The dual cost function can be obtained from this equation:

$$PS_i = \frac{1}{A_0} [\alpha^{d\sigma} PD_i^{1-\sigma} + \alpha^{m\sigma} M_i^{1-\sigma}]^{1/1-\sigma} \quad (A57)$$

The total value of domestic supply is, in this case:

$$VQS_i = PS_i DS_i = PD_i DC_i + PM_i M_i \quad (A58)$$

For domestic buyers, the prices of imported commodities are equal to the prices at foreign currency (PM_i^*) plus tariffs, VAT and *ad valorem* carbon taxes, multiplied by exchange rates (e).

$$PM_i = e(1 + t_i^m + t_i^{vat} + t_i^{mv})PM_i^* + t_i^{mc} \quad (A59)$$

A constant elasticity of transformation function (CET) allocates domestically produced commodities between domestic consumption (DC_{it}) and exports (X_{it}), using an elasticity of transformation (σ_i^e) and the shares of exported commodities obtained from the SAM (α_{it}^x):

$$QC_{it} = k_{it}^x \left[\alpha_{it}^x X_{it}^{\frac{\sigma_i^e - 1}{\sigma_i^e}} + (1 - \alpha_{it}^x) DC_{it}^{\frac{\sigma_i^e - 1}{\sigma_i^e}} \right]^{\frac{\sigma_i^e}{\sigma_i^e - 1}} \quad (A60)$$

Export prices, export demand and value equations can be expressed, including export subsidies (s_{it}^e):

$$PX_{it} = e_t(1 + s_{it}^e)PE_{it}^* \quad (A61)$$

$$X_{it} = DC_{it} \left[\frac{1 - \alpha_{it}^x}{\alpha_{it}^x} \frac{PD_{it}}{PX_{it}} \right]^{\sigma_i^e} \quad (A62)$$

$$PC_{it}QC_{it} = PD_{it}DC_{it} + PX_{it}X_{it} \quad (A63)$$

The current account balance (CA) is set exogenously and modelled through the total value of exports, the total value of imports, the value of net capital incomes transferred abroad (NFY), net government payments transferred abroad (G_{IR}) and net transfers from the rest of the world to households ($R_{Transfer}$):

$$CA = \sum_i \frac{PX_i X_i}{(1 + s_i^e)} - \sum_i ePM_i^* M_i - NFY - G_{IR} + R_{Transfer} \quad (A64)$$

A.6. Markets

Markets in equilibrium adjust supply and demand of all commodities, of labour, of capital and of land, obtaining the relative prices of these commodities and factors. In the base case all prices are equal to 1, and they change to adjust to external shocks, to rebalance markets, i.e. the whole equation system. Commodity markets in equilibrium are represented by this equation, showing that domestically supplied commodities must be equal to intermediate demands plus final consumption of households and government plus investment:

$$DS_i = \sum_j A_{ij} + C_i + G_i + I_i \quad (A65)$$

Labour is mobile across sectors, so there is an average wage which balances labour supply and demand. This wage is allocated with wage distribution coefficients (ψ_{jt}^L). Similarly, capital market uses capital rental price distribution coefficients (ψ_{jt}^K), and land is set exogenously:

$$\sum_j \psi_{jt}^L LD_{jt} = LS_t \quad (A66)$$

$$KD_{jt} = \sum_j \psi_{jt}^K K_{jt} \quad (A67)$$

$$TD_j = T_j \quad (A68)$$

On the other hand, investments are equal to savings in this model:

$$S^P + RE + G_{INV} = II + \Delta G + CA \quad (A69)$$

A.7. Energy and CO₂ emissions

The economic model described includes two submodules: an energy and an environmental module. In this version of the model, the environmental module only accounts for CO₂ emissions, although the same methodology can be extended to other kind of pollutants if data are available. In this model we implement a top-down approach to account for the energy use and carbon emissions along the economic system. A bottom-up approach can also be used. Both are discussed in Jorgenson et al. (2018) and converge to provide the same result. More details on this method can be found in Cao and Ho (2017).

In summary, the energy used by the economic system is obtained with information in the use matrix of different energy products bought by different industries. This matrix provides the economic flows in euros. These flows are transformed into quantities (tons) of energy products thanks to the information provided by the energy balances for Catalonia for 2014 from the Catalan Energy Institute (ICAEN). Then, another coefficient, or conversion factor, transforms these quantities into energy flows, and another one into carbon emissions. These are obtained from the International Energy Agency (IEA). General equations for the different energy sources are:

$$EN = \sum_i e_i q_i (QC_i - X_i) + \sum_i e_i q_i M_i \quad (A70)$$

$$CO_2 = \sum_i c_i e_i q_i (QC_i - X_i) + \sum_i c_i e_i q_i M_i \quad (A71)$$

where q_i are quantity coefficients (tons/euro) for energy source i , or m³/euro for gas; e_i are energy coefficients (joules/tones) for source i , or joules/m³ for natural gas; and c_i are emission coefficients (tons of CO₂/joule) for source i . Therefore, EN is total energy used by the economic system, and CO_2 are total carbon emissions.

Appendix II. Elasticities used in the model for the base case and the different scenarios in behavioural equations.

Table A1. Elasticities used in the model and sources.

Elasticity	Symbol and value	Source
Non-energy intermediate inputs	$\sigma_{jt} = 1$	Cobb-Douglass production functions
KLT composite	$\sigma_{jt}^{VA} = 0.2 - 1.68$	Hertel et al. (2014)
Energy intermediate inputs composite	$\sigma_{jt}^E = 0.5$	Ross (2007)
(KLT)E composite	$\sigma_{jt}^{VE} = 0.5$	Ross (2007)
(KLTE)M composite	$\sigma_{jt}^{QI} = 0.15$	Cao et al. (2019)
Domestic and imported goods composite (CES)	$\sigma_i^m = 0.571 - 2.020$	Aspalter (2016) / Németh et al. (2011)
Domestic and exported goods composite (CET)	$\sigma_i^e = -1.926$	Imbs and Mejean (2010)

Appendix III. Detailed results of directing energy expenditures to each one of the non-energy and energy commodities included in the Catalan SAM.

Table A2. GDP variation, CO2 variation and energy rebound effect, for year 1 and year 20, in relation to the base case, where 25% of energy expenditures are re-spent in each of the other 60 non-energy commodities of Catalan SAM.

Sector	Initial weight in households' budget	Year 1			Year 20		
		GDP variation	CO2 variation	Energy rebound effect	GDP variation	CO2 variation	Energy rebound effect
Agriculture, livestock and hunting	1.2132%	-0.1643%	-9.16%	64.90%	-0.0053%	-8.72%	65.99%
Products of forestry, logging and related services	0.0286%	-0.3980%	-9.13%	65.01%	-0.1577%	-8.66%	66.25%
Fish and other fishing products	0.2529%	-0.1330%	-9.13%	65.02%	0.1078%	-8.75%	65.91%
Other mining (except energy products)	0.0050%	-0.1684%	-9.26%	64.62%	-0.3624%	-9.58%	63.21%
Food products, beverages and tobacco	7.2715%	-0.1796%	-9.19%	64.79%	-0.0798%	-9.00%	64.92%
Textiles	1.8351%	-0.1005%	-9.19%	64.79%	0.0818%	-8.93%	65.23%
Wood, and products of wood and cork	0.0429%	-0.2016%	-9.30%	64.36%	-0.1277%	-9.24%	64.05%
Paper and paper products	0.1728%	-0.1994%	-8.95%	65.69%	-0.1933%	-8.60%	66.42%
Printed matter and recorded media	0.0007%	-0.2928%	-9.35%	64.20%	-0.2425%	-9.21%	64.14%
Chemical products	0.3980%	-0.1379%	-7.31%	71.77%	0.0420%	-5.50%	77.90%
Pharmaceutical products	0.4164%	-0.0994%	-9.17%	64.86%	0.1427%	-8.58%	66.48%
Rubber and plastic products	0.0573%	-0.1932%	-8.69%	66.63%	-0.1838%	-7.64%	69.93%
Other non-metallic mineral products	0.0566%	-0.2732%	-8.58%	66.94%	-0.3749%	-8.50%	66.61%
Basic metals	0.0006%	-0.1833%	-9.05%	65.36%	-0.1468%	-8.82%	65.70%
Fabricated metal products, except machinery	0.0798%	-0.2695%	-9.31%	64.35%	-0.2809%	-9.27%	63.92%
Computers and electronic equipment	0.3699%	-0.0680%	-9.24%	64.60%	-0.0358%	-9.05%	64.70%
Electric machinery	0.3906%	-0.1561%	-9.24%	64.62%	-0.1168%	-9.02%	64.86%
Machinery and apparatus n.e.c.	0.0153%	-0.1923%	-9.31%	64.31%	-0.0555%	-9.12%	64.48%

Motor vehicles, trailers and semi-trailers	1.5622%	-0.1501%	-9.19%	64.79%	-0.0817%	-8.88%	65.36%
Other transport equipment	0.1742%	-0.2287%	-9.31%	64.32%	-0.1513%	-9.10%	64.54%
Furniture and other manufactured products	0.7552%	-0.1580%	-9.36%	64.15%	0.0092%	-9.29%	63.83%
Repair of machinery and equipment	0.0000%	-0.2900%	-9.48%	63.69%	-0.0298%	-9.19%	64.22%
Services of water	0.4081%	-0.3748%	-9.23%	64.79%	-0.5605%	-9.54%	63.10%
Waste services	0.2815%	-0.4323%	-9.34%	64.16%	-0.4270%	-9.38%	63.36%
Construction	0.9875%	-0.2851%	-9.37%	64.08%	-0.3913%	-9.42%	63.22%
Sale, maintenance and repair of motor vehicles	1.9576%	-0.4405%	-9.80%	62.50%	-0.0776%	-9.51%	63.08%
Wholesale trade	3.7697%	-0.5010%	-9.52%	63.55%	-0.3184%	-9.51%	63.09%
Retail trade services	9.7597%	-0.3791%	-9.41%	63.99%	-0.0942%	-9.25%	64.14%
Land transport	1.9674%	-0.3487%	-7.77%	70.09%	-0.2820%	-7.63%	69.94%
Water transport	0.0470%	-0.2437%	-9.34%	64.20%	-0.1377%	-9.18%	64.21%
Air transport	0.6008%	-0.2303%	-2.91%	88.17%	-0.1805%	-3.06%	86.61%
Auxiliary transport activities	1.4266%	-0.4047%	-9.76%	62.61%	-0.2650%	-9.48%	63.09%
Post and courier services	0.0032%	-0.4582%	-9.37%	64.06%	-0.4847%	-9.37%	63.45%
Hotel and restaurant services	14.4661%	-0.3724%	-9.35%	64.22%	0.1035%	-9.10%	64.69%
Editing services	0.4157%	-0.4330%	-9.56%	63.36%	-0.4681%	-9.81%	61.77%
Cinema, video, radio, TV	0.4250%	-0.2645%	-9.59%	63.25%	-0.2488%	-9.31%	63.75%
Telecommunications services	2.1410%	-0.2258%	-9.28%	64.47%	-0.1003%	-9.24%	64.05%
Information and ICT	0.0000%	-0.3720%	-9.52%	63.49%	-0.4134%	-9.60%	62.54%
Financial services, except insurance and pension funding	1.5645%	-0.3252%	-9.53%	63.46%	0.0764%	-9.29%	63.86%
Insurance and pension funding services, exc. compulsory SS	1.3565%	-0.1330%	-9.38%	64.04%	0.3103%	-9.09%	64.60%
Services auxiliary to financial intermediation	0.6281%	-0.3626%	-9.21%	64.68%	0.2753%	-8.89%	65.38%
Real estate activities	19.5866%	-0.3265%	-9.21%	64.71%	0.5826%	-8.86%	65.52%
Legal, accounting and consulting	0.0103%	-0.2999%	-9.52%	63.49%	-0.1208%	-9.43%	63.24%
Architectural and engineering technical	0.0811%	-0.3965%	-9.26%	64.47%	-0.2178%	-9.21%	64.06%
Research and development	0.0000%	-0.3007%	-9.40%	63.99%	-0.1257%	-9.51%	62.95%
Advertising services and market research	0.0000%	-0.2225%	-9.36%	64.14%	-0.0641%	-9.16%	64.30%

Other professional and technical services; veterinarians	0.2167%	-0.3999%	-9.44%	63.80%	-0.0749%	-9.39%	63.44%
Rental services	0.2710%	-0.3749%	-9.68%	62.95%	0.0028%	-9.31%	63.74%
Employment-related services	0.0000%	-0.3689%	-9.70%	62.82%	-0.1446%	-9.58%	62.65%
Services travel agencies and tour operators	0.8206%	-0.3892%	-8.53%	67.22%	-0.1059%	-8.36%	67.26%
Security	0.0436%	-0.3409%	-9.57%	63.31%	-0.2925%	-9.36%	63.54%
Services: public administration, defence and compulsory SS	0.0709%	-0.1330%	-9.50%	63.60%	-0.4826%	-9.58%	62.73%
Education services	3.3051%	-0.3289%	-9.62%	63.11%	-0.3078%	-9.51%	62.93%
Health care services	4.3368%	-0.3119%	-9.49%	63.61%	-0.1067%	-9.30%	63.76%
Social services	0.6755%	-0.3357%	-9.48%	63.64%	-0.4668%	-9.56%	62.73%
Artistic and cultural services	2.5144%	-0.3592%	-9.40%	63.99%	-0.4296%	-9.65%	62.37%
Sports, recreation and entertainment	1.4126%	-0.5101%	-9.35%	64.20%	-0.6499%	-9.68%	62.32%
Services provided by associations	0.0000%	-0.3348%	-9.44%	63.82%	-0.3628%	-9.40%	63.38%
Computer repair, personal and household goods services	0.2901%	-0.2499%	-9.49%	63.61%	-0.3119%	-9.57%	62.68%
Other personal services	3.2990%	-0.3251%	-9.46%	63.75%	-0.4494%	-9.64%	62.41%

Table A3. GDP variation, CO₂ variation and energy rebound effect, for year 1 and year 20, in relation to the base case, where 5% of specific energy expenditures are re-spent in other energy commodities of Catalan SAM.

Re-spending	Initial weight in households' energy expenditures	Year 1			Year 20		
		GDP variation	CO2 variation	Energy rebound effect	GDP variation	CO2 variation	Energy rebound effect
Oil → natural gas	55.06%	-0.0299%	-0.4567%	61.67%	-0.0688%	-0.4725%	61.41%
Oil → electricity	55.06%	-0.0199%	-1.4098%	61.16%	-0.0390%	-1.3482%	61.38%
Natural gas → oil	8.35%	0.0316%	0.4276%	117.49%	0.0774%	0.4722%	115.78%
Natural gas → electricity	8.35%	0.0128%	-0.9862%	97.05%	0.0403%	-0.8769%	98.11%
Electricity → oil	36.59%	0.0198%	1.4077%	63.15%	0.0404%	1.3493%	60.08%
Electricity → gas	36.59%	-0.009%	0.9475%	64.49%	-0.0265%	0.8760%	59.41%