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Policy strategies to tackle rebound effects: A comparative analysis

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ABSTRACT

Promoting energy efficiency is generally assumed to be an effective strategy to reduce energy use and tackle climate change. However, an extensive literature has shown that rebound effects reduce its effectiveness and can even be counterproductive. We show how a more complex policy strategy, with coordinated measures, could provide the desired results by offsetting energy and carbon rebound effects. Along with the energy-efficiency improvement, we separately implement five different policies: carbon taxes, energy production taxes, an emissions trading system, and changes in consumption patterns (away from energy and toward services consumption). These policies are assessed using an economy–energy–environment dynamic Computable General Equilibrium (CGE) model developed for Catalonia, and compared in economic, energy, and environmental terms. The simulations show that all the strategies tested are able to offset rebounds at a low cost, with a proper design. All of them improve GDP in relation to the no-efficiency improvement base case. If tax revenues from the parallel policies are used to encourage investment, the long-term effect on GDP may even be positive.

1. Introduction

A key issue in economics, sustainability science, and related areas is the secondary effects of economic and environmental policies and how to deal with them. Research on rebound effects from higher energy efficiency and the Jevons' Paradox supports the complexity of policy decision-making by confronting objectives with actual results. The rebound effect of energy efficiency and conservation highlights the difference between expected and actual energy savings. Empirical evidence shows that policies aiming at reducing energy use by simply fostering energy efficiency or conservation may not be as effective as expected (Brookes, 1979; Khazzoom, 1980; Berkhout et al., 2000; Binswanger, 2001; Sorrell, 2007; Freire-González, 2011; Font Vivanco et al., 2016b). In some cases, they can even be counterproductive, increasing final energy consumption. This extreme case is known as the Khazzoom-Brookes postulate, Jevons' Paradox, or "backfire" (Saunders, 1992). This problem is extensive for other natural resources, not just energy (Freire-González and Font Vivanco, 2017).

After four decades of studies on this phenomenon, there is a strong consensus among scholars as to the existence of rebounds, but there is still no consensus on its magnitude or its real impact on sustainability efforts. The rebound effect generates, in the best case, a problem of effectiveness of energy policies, of resource and climate policies, and of efficiency in the use of public resources. In recent years, some researchers have suggested and analyzed potential solutions from a conceptual or theoretical perspective (van den Bergh, 2011, 2015; Santarius, 2012; Freire-González and Puig-Ventosa, 2015; Font Vivanco et al., 2016a). However, the evidence for different measures in offsetting rebounds is scarce and scattered. Kratena et al. (2010) estimated the energy tax levels to avoid rebound effects in Austria, with tax levels between 7% and 60%. Saunders (2018) analyzed the potential of energy taxation to limit the rebound effect and found tax levels from 10% to more than 300% are required, depending on the economic sector levied. Freire-González (2020), using a Computable General Equilibrium (CGE) model for the Spanish economy, showed how energy taxes can be used to counteract the economy-wide rebound effect and found an energy tax rate of 3.76% for the Spanish economy. These few studies are focused on environmental/energy taxation, but there is no literature we could find on the effects of other instruments in limiting or counteracting rebounds such as emissions trading systems (ETS) or behavioral changes.

The objective of this research is threefold: first, assess the effectiveness of different economic and policy instruments identified in the literature as offsetting rebounds; second, quantitatively find the effort needed for each instrument to offset rebounds in terms of tax rates, emissions targets, or relative changes in consumption patterns; and third, compare them in terms of economic impact, energy use, and

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carbon emissions. To achieve the objective, we develop an economy–energy–environment recursive-dynamic CGE model for the Catalan economy. This is the first study, to the best of our knowledge, to assess the potential effectiveness and economic impact of a set of different instruments in avoiding rebound effects and compare them within the same framework. We establish and analyze the implementation of six different scenarios or policy strategies: (1) energy efficiency promotion with no additional policies or measures, (2) energy efficiency plus carbon taxes, (3) energy efficiency plus energy production taxes, (4) energy efficiency plus ETS, (5) energy efficiency plus energy conservation in households, and (6) energy efficiency plus a shift to services consumption in households. These are 3 market-based and two behavioral strategies suggested in previous work including van den Bergh (2011, 2015), Santarius (2012), Freire-González and Puig-Ventosa (2015) and Font Vivanco et al. (2016a).

The structure of the article is as follows: in section two we detail the methodology followed to develop the economy–energy–environment CGE model for Catalonia; in section three we show the policy scenarios assessed in the model; in section four we analyze and discuss the main results; and in section five we provide conclusions.

2. Methodology

Our methodology is implemented in five steps: (1) developing an economy–energy–environment recursive dynamic CGE model for Catalonia, (2) obtaining the energy and carbon rebound effect estimates, (3) identification of different policy strategies with potential for counteracting rebound effects, (4) a quantitative design of the optimal values for each policy strategy, (5) simulation of policies and comparing results in terms of energy use, carbon emissions, and different aggregate and sector-level economic indicators.

We first project a base case path of the economy where there is no special energy efficiency improvement using a model of Catalonia described in section 2.1 (and Appendix I). The data, parameters and exogenous variables of the base case is given in section 2.2. We then simulate the impact of an autonomous improvement in energy efficiency. Policy cases incorporate this improvement and include the parallel policies described in section 3.

2.1. The economy–energy–environment recursive dynamic CGE model

The model is based on Freire-González and Ho (2019) model of Spain which draws on Jorgenson et al. (2013), and Cao et al. (2019). Various specific features and adaptations for the Catalan economy are adopted in constructing this model. The full details of the model with all the equations, variables, and parameters are in Appendix I.

The model is essentially a set of behavioral equations that describe the economic flows among four different economic agents: firms, government, households, and the foreign sector. There are 64 economic sectors and 64 groups of commodities. It also includes a great amount of detail on taxes, including value-added tax (VAT), special taxes, subsidies, other taxes on production, tariffs, VAT on imports, and social security contributions.

Production functions of the 64 sectors included are represented by nested constant elasticity substitution (CES) equations. The nested structure has three different levels (see Fig. 1). On the first level, or lowest in the nesting structure, capital, labor, and land combine to generate value added (VA); energy sectors (extraction of energy products; refinement of petroleum; production and distribution of electricity; and production and distribution of natural gas) combine to generate an energy (E) aggregate. On the second level, VA and E combine to produce another composite (VE), and non-energy intermediate inputs combine using Cobb-Douglas production functions to produce (M), a composite. At the top level of the nesting structure, the VE composite and M are combined to generate the industry output (QI).

It is an open, single-country model. We model imports, including them in the domestic supply, following an Armington (1969) approach with a CES function between domestically produced commodities and imports. Exports are modeled by considering constant elasticity of transformation (CET) functions, which distribute domestically produced commodities between exports and the domestic market.

There is also an energy module linked to an environmental module where economic flows, described in the input-output relationships of the social accounting matrix, are transformed into energy and carbon emissions flows. This consist of energy and emission coefficients generated with information from different sources. The model includes the actual percentage of renewables for the period 2014–2017 in Catalonia, and this share is projected using a logarithmic function over the simulation horizon. If renewables grow faster than this projection, the carbon rebound effect may be overestimated for shocks involving reductions in electricity use, but not the energy rebound effect. The energy and environmental modules follow the same accounting method used in Freire-González and Ho (2018, 2019).

This is a Solow growth model with exogenous saving rates, and growth is driven by capital accumulation, growth of population and total factor productivity (TFP). Capital accumulation depends on the depreciated capital stock of previous periods plus the investments of the current period, which is financed by private savings. This module allows the simulation over different periods. We simulated a 20-year period for all the scenarios to observe how the different policy strategies evolve dynamically as well as their long-term effects.

2.2. Data

2.2.1. The social accounting matrix (SAM)

Table 1 shows a summary of the Catalan SAM used to calibrate the model. We obtained input–output tables (supply and use tables) for 2014 from the Statistical Institute of Catalonia (IDESCAT). Sector employment, labor and capital compensation also come from the input–output framework. Government and social security accounts are from the Ministry of the Vice-Presidency and of the Economy and Finance of Catalonia and the General Comptroller of the State Administration of Spain. Capital stock data comes from the BBVA Foundation (Mas Ivars et al., 2018). Accounts for firms have been obtained from the Bank of Spain.

2.2.2. Energy and CO_2 emissions data

Data on the consumption of coal, oil, natural gas, and electricity are from the energy balances of Catalonia for 2014 and from the Catalan Energy Institute. Different conversion factors for energy and carbon emissions for the fossil fuels are obtained from the International Energy Agency.

2.2.3. Parameters and exogenous variables

Exogenous variables in the model are population, obtained from the IDESCAT; working-age population (for which we have assumed the same growth path as the population); dividend rates; saving rates; current account deficits; and government deficits. These variables are obtained from the SAM, and we assume stability during the simulation period. TFP growth is also exogenous and calibrated to deliver a 2% GDP annual growth rate in the base case. The values chosen for the different elasticities used in the model and their sources are given in Appendix I.

2.3. Rebound effect estimates

We estimate two kinds of rebound effects: the energy rebound effect (ERE) and the carbon rebound effect (CRE). For each of the policy scenarios, the rebound effect comes from the difference between the expected energy use or carbon emissions derived from partial equilibrium

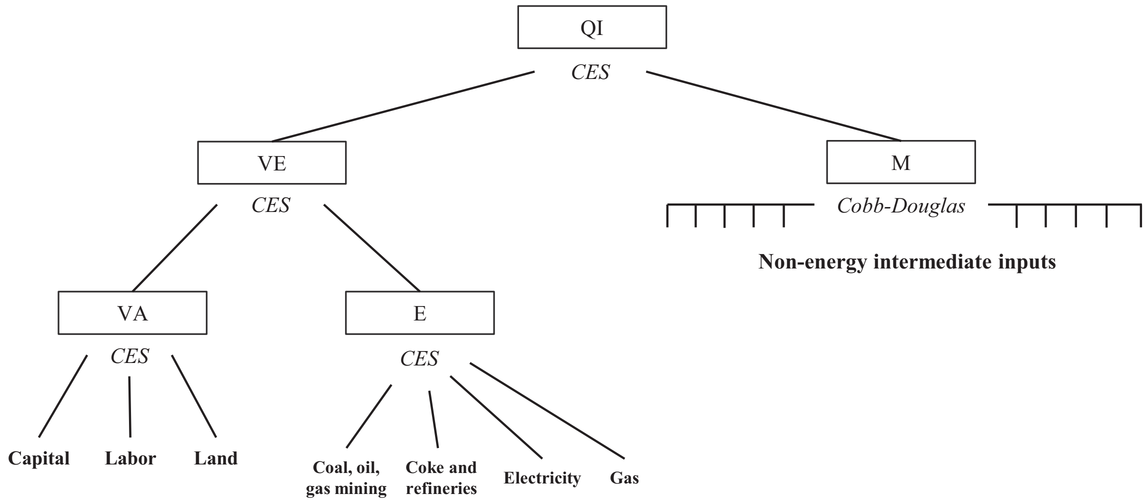

Fig. 1. Nested structure of the production module in the Catalan economy–energy–environment CGE model.
Source: own elaboration

analysis and the actual general equilibrium energy use or carbon emissions. The economy-wide rebound effect can be formulated in general terms as follows[1]:

$$RE = \left[1 + \frac{\dot{E}}{\rho}\right] \times 100 \tag{1}$$

where $\dot{E}$ is the actual change in energy use and ρ is the rate of energy augmenting technical progress, or energy efficiency improvement. For simplicity we keep ρ constant for all years in the simulation horizon.

This formulation accounts for the total energy use in the modeled economy and a correction is needed if energy efficiency only occurs in a subset of energy uses. From Turner (2008), this correction can be formulated as:

$$RE = \left[1 + \frac{\dot{E}}{\gamma\rho}\right] \times 100 \tag{2}$$

$$\gamma = \frac{E_{I(D)}}{E_T} \tag{3}$$

where γ is the share of energy uses affected by the efficiency improvement and the T, I, and D subscripts mean total, industry, and domestic supplied energy, respectively. In this study, energy efficiency improvements are simulated for the energy used in domestic production processes and we include this. To focus on domestic effects, we assume that there is no corresponding efficiency improvement in the rest of the world. If there were identical global improvements, then the relative prices of imports may be different depending on the industry production functions of each country.

In this framework, the main objective is to know how total energy use changes after an efficiency improvement in a general equilibrium context. Turner (2008) gives some theoretical insights. A change in energy efficiency can be seen as an impact on the price of energy measured in efficiency units:

$$\dot{p}_{\varepsilon} = \dot{p}_E - \rho \tag{4}$$

where $\dot{p}_{\varepsilon}$ is the change in energy price in efficiency units, $\dot{p}_E$ is the change in the price of energy, and ρ is the rate of energy augmenting technical progress. The change in energy use, measured in efficiency units ($\dot{\varepsilon}$), is equal to the change of energy prices in efficiency units, multiplied by the general equilibrium (negative) price elasticity of the demand for energy ($-\vartheta$). At the same time, energy in natural units ($\dot{E}$) is equal to energy use in efficiency units ($\dot{\varepsilon}$) minus the rate of energy augmenting technical progress:

$$\dot{\varepsilon} = -\vartheta\dot{p}_{\varepsilon} \tag{5}$$

$$\dot{\varepsilon} = \rho + \dot{E} \tag{6}$$

From Eqs. (4), (5), and (6), we can find the change in energy use after an energy efficiency improvement from this equation:

$$\dot{E} = (\vartheta - 1)\rho \tag{7}$$

So, the change in total energy use after an efficiency or productivity improvement will ultimately depend on the general equilibrium price elasticity of the demand for energy.

3. Scenarios

The main target of the different scenarios is to offset the general equilibrium rebound effect in each of the 20 years of the simulation. From Eq. (2), if the rebound effect is equal to zero, the change in total energy use must be set at:

$$0 = \left[1 + \frac{\dot{E}_s}{\gamma\rho}\right] \times 100 \tag{8}$$

$$\dot{E}_{ECTS} = -\gamma\rho \tag{9}$$

where $\dot{E}_s$ is the energy target in scenario s. The economic system reduces total energy use at the same rate as that of the energy efficiency improvement. We define six different scenarios in this study along with the base case. They can be classified into three big policy strategies: environmental taxation, ETS, and changes in lifestyles or consumption patterns: (1) energy efficiency improvement with no additional policies (E-NP); (2) energy efficiency plus carbon taxes (E-CT); (3) energy efficiency plus energy production taxes (E-ET); (4) energy efficiency plus ETS (E-ETS); (5) energy efficiency plus energy conservation in households (E-HHE); and (6) energy efficiency plus an increase in services consumption in households (E-HHS).

Additionally, to facilitate comparisons within scenarios and reduce the economic costs of the policies, we implement fiscal neutrality in the tax and ETS scenarios by recycling the carbon revenues. Specifically, we use revenues to reduce capital taxes, VAT, and sales taxes proportionally, although other combinations/recycling possibilities toward these

[1] An analogous procedure is followed for the carbon rebound effect.

Table 1
Catalan SAM 2014, million euros.

	Commodity	Industry	Labor	Capital	Land	Households	Enterprise	Government	Taxes less subs. on products	Other taxes on prod.	Social security	Tariff	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**
Labor		104,064.0														**104,064.0**
Capital		82,256.6														**82,256.6**
Land		1335.4														**1335.4**
Households			80,279.0		1335.4		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	2951.7	23,785.0	276.0	4212.6	−8406.6		**68,978.1**
Taxes less subs. on products		11,755.9														**11,755.9**
Other taxes on prod.		2951.7														**2951.7**
Social security			23,785.0													**23,785.0**
Tariff	276.0															**276.0**
VAT for import	4212.6															**4212.6**
Capital a/c						26,181.6	3353.5	1708.3							−3670.9	**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**	**1335.4**	**161,757.3**	**81,820.6**	**68,978.0**	**11,755.9**	**2951.7**	**23,785.0**	**276.0**	**4212.6**	**27,572.4**	**135,153.5**	

Source: own elaboration.

or other preexisting taxes would also be useful for comparison and would improve the economic results in relation to non-recycling scenarios (e.g., Freire-González and Ho, 2018).

Because government deficits are equal to base case levels, real government spending must remain the same as in the base case. To scale the actual tax rates in the policy cases, we introduce an additional endogenous variable λ_t into the equation system:

$$t_{jt}^{w;P} = \lambda_t \, t_{j0}^{w} \tag{10}$$

in which $t_{jt}^{w;\,P}$ is the tax rate for tax w in sector j under the policy strategy (P); the 0 subscript is for base case values. To keep aggregate government purchases neutral, we add a restriction in the policy scenarios:

$$GG_P(t) = GG_{base}(t) \tag{11}$$

GG is the quantity of aggregate government purchases (an index over commodities). Tax rates become endogenous in the policy scenarios by multiplying preexisting taxes by the scale variable (λ_t).

3.1. Energy efficiency with no additional policies scenario (E-NP)

This scenario simulates an exogenous increase of energy efficiency. There are no additional control policies and there may be rebound effects. We follow the approach proposed by Turner (2008), which is similar to the one applied by Grepperud and Rasmussen (2004), Freire-González (2020), and others, for the estimation of the economy-wide rebound effect.

As detailed in Appendix I, production is described in the model using nested CES functions with constant returns-to-scale. Given we assume a uniform efficiency increase for all the energy inputs, energy productivity improvements can be set at the energy composite level (E in Fig. 1) of the nesting structure. The input demand function is represented in the model as:

$$E_{jt} = \left(\frac{1}{k_{jt}^{VE}}\right)^{1-\sigma_{jt}^{VE}} \left[\alpha_{E_{jt}} \frac{P_{jt}^{VE}}{PE_{jt}}\right]^{\sigma_{jt}^{QI}} VE_{jt} \tag{12}$$

where E_{jt} is the quantity of the energy composite used by industry j at period t; $\alpha_{E_{jt}}$ is the share for all energy inputs into industry j at period t; VE_{jt} is the quantity of the value-added energy composite used by industry j at period t; and $1/\sigma_{jt}^{VE}$ is the elasticity of substitution between the two inputs. The weights of the function ($\alpha_{E_{jt}}$ and k_{jt}^{VE}) are obtained from a calibration process, using the base case data.[2] The dual cost function expresses the price of this composite (PE_{jt}) as a function of the four component energy prices:

$$PE_{jt} = \frac{1}{k_{jt}^{E}} \left[\sum_{k \in IE} \alpha_{k_{jt}}^{E\sigma_{jt}^{E}} PB_{k_{jt}}^{\left(1-\sigma_{jt}^{E}\right)}\right]^{\frac{1}{1-\sigma_{jt}^{E}}} \qquad IE = \{EnEx, Coke, EnEle, Prodgas\} \tag{13}$$

where PB_{kjt} is the price of the energy input of type k, k = energy extraction (EnEx), petroleum and Coke (Coke), electricity (EnEle), and gas utilities (Prodgas). Following Grepperud and Rasmussen (2004), the annual average growth of energy productivity can be explicitly included in these equations with a new parameter ($\phi_{E_{jt}}$):

$$E_{jt} = \left(\frac{1}{k_{jt}^{VE}}\right)^{1-\sigma_{jt}^{VE}} \left[\alpha_{E_{jt}} \frac{P_{jt}^{VE}}{\phi_{E_{jt}} PE_{jt}}\right]^{\sigma_{jt}^{QI}} VE_{jt} \tag{14}$$

$$\phi_{E_{jt}} PE_{jt} = \frac{1}{k_{jt}^{E}} \left[\sum_{k \in IE} \alpha_{k_{jt}}^{E\sigma_{jt}^{E}} PB_{k_{jt}}^{\left(1-\sigma_{jt}^{E}\right)}\right]^{\frac{1}{1-\sigma_{jt}^{E}}} \quad IE = \{EnEx, Coke, EnEle, Prodgas\} \tag{15}$$

[2] For more details on the calibration process, see Rutherford (2003) and Klump et al. (2011).

Energy efficiency changes are introduced by modifying the $\phi_{E_{jt}}$ parameter. In the base case, it is equal to one, while in this *E*-NP scenario and all the other policy scenarios, we set $\phi_{E_{jt}} = 1.05\phi_{E_{jt-1}}$, that is, a 5% increase in the productivity for all the energy inputs in each period of the simulation. When running the model with this new value, the whole equation system rebalances to obtain a new equilibrium with new values for the different macroeconomic, energy, and climate variables of interest compared to the base case. We represent the technology change in this cost-free manner since it is the simplest, transparent, method. Energy efficiency improvements may come from deliberate efforts at research and development which is costly. These R&D costs should be considered in future research.

3.2. Energy efficiency plus carbon taxes scenario (E-CT)

This scenario includes two exogenous and simultaneous shocks: an energy efficiency improvement of 5% each year, in the same way as just described for scenario *E*-NP, and a carbon tax that totally offsets the rebound effect provoked by this efficiency increase. The approach used to model the carbon tax can be found in Freire-González and Ho (2019), where the carbon tax per unit of fuel *j* is:

$$t_j^c = t^x \theta_j \tag{16}$$

In this equation, t^x is the unitary carbon tax in euros per ton of carbon, and θ_j is the carbon emissions coefficient per unit of fuel *j* expressed in tons per (constant) euro. The carbon tax is levied every year of the simulation, adjusted by the GDP deflator. It triggers changes in relative prices of commodities and revenues to the government. Appendix I shows the specific interactions of the carbon tax within the economic system modeled.[3] The aim is to obtain the same total energy use (or carbon emissions) as in the base case including $-\gamma\rho$ (see Eq. (9)), with fiscal neutrality as described earlier.

3.3. Energy efficiency plus energy production taxes scenario (E-ET)

This scenario is similar to E-CT but implements energy production taxes instead of a carbon tax. This scenario also includes two simultaneous shocks: the first comprises an exogenous energy efficiency improvement of 5% (see *E*-NP). The second shock consists of implementing an output tax on (final) energy production sectors to offset the rebound triggered by the first shock. Specifically, an *ad valorem* tax to the production of the different final energy production industries has been levied, following the approach described in Freire-González (2020). These industries are threefold in our SAM: production of coke and petroleum refining, production and distribution of electricity, and production and distribution of gas; energy extraction industries are not taxed. The same tax rate has been applied to all these domestic industries and their imports. As in the other policy scenarios, the aim is to obtain the same energy use (or carbon emissions) as in the base case, implementing fiscal neutrality.

3.4. Energy efficiency plus ETS scenario (E-ETS)

This scenario also includes two shocks: an exogenous energy efficiency improvement of 5%, the same way as carried out in E-NP and, simultaneously, a cap on carbon emissions on specific industries, simulating a carbon emissions cap-and-trade system or ETS. We follow a similar approach as specified in Cao et al. (2019), implementing an ETS for six different energy-intensive industries: paper and paper products, production of coke and refinement of petroleum, chemical products, other nonmetallic mineral products, basic metals, and production and distribution of electricity. These 6 industries account for 43.54% of Catalan CO_2 emissions when we include the CO_2 embodied in the electricity they consume. The ETS is implemented by including into the economic model a carbon price, paid by industries covered by the emissions system, and exempted for all the other industries:

$$PB_{ijt} = PS_{it} + t_{ijt}^{xCO2}\, \rho_{ij}^{cmb} \tag{17}$$

$$t_{ijt}^{xCO2} = \begin{cases} t_{itj}^{xCO2}\ j \in covered\ industry \\ 0\ j \in non-covered\ industry \end{cases} \tag{18}$$

$$t_{ijt}^{xCO2} = tx_{CO2,t}^{u}\, XP_{ijt}^{CO2} \tag{19}$$

where PB_{ij} is the price of intermediate input *i* for industry *j* with ETS; PS_{it} is the supply price without the ETS; t_{ijt}^{xCO2} is the total carbon price; ρ_{ij}^{cmb} are combustion ratios[4]; $tx_{CO2,\ t}^{\ u}$ is the unit carbon price; and XP_{ijt}^{CO2} is the emissions intensity coefficient (i.e., emissions per unit of output in tons/euros). Carbon emissions embodied in electricity also require an emission permit and is set as follows: the amount of embodied CO2 is set by a carbon emissions factor for electricity ($XP_{elec,\ t}^{\ CO2}$), and this factor is projected to decline over time when the renewables share in electricity generation grows. The price of electricity for the covered sectors is then:

$$PB_{elec,jt} = PS_{elec,t} + t_{elec,jt}^{CO2} \tag{20}$$

$$t_{elec,jt}^{xCO2} = \begin{cases} t_{elec,t}^{xCO2}\ j \in covered\ industry \\ 0\ j \in non-covered\ industry \end{cases} \tag{21}$$

$$t_{elec,jt}^{xCO2} = tx_{CO2,t}^{u}\, XP_{elec,jt}^{CO2} \tag{22}$$

The total carbon permits needed by an industry are the sum of the direct emissions of combustion of hydrocarbons and the indirect emissions from electricity required. Process emissions of the cement industry have also been included in the ETS so this industry also needs to buy allowances for these emissions to carry out its activity. Total carbon emissions (*EM*) for industry *j* are:

$$EM_{jt} = \sum_{i \in I_{COM}^{CO_2}} \rho_{ij}^{CO_2} XP_{it}^{CO_2} A_{ijt} + XP_{elec,t}^{CO_2} A_{elec,jt} + \left[XP_{cem,t}^{CO_2} QI_{cem,t}\ for\ j = cement \right], \tag{23}$$

where *XP*'s are the various emissions coefficients that transform economic flows into carbon emissions; A_{ij} is the quantity of intermediate input *i* to industry *j*; and QI_j is the production of industry *j*. A cap on emissions (CAP^{CO_2}) is imposed on the covered sectors:

$$\sum_j EM_{jt} \le CAP^{CO_2} \tag{24}$$

The cap is chosen such that the overall energy rebound, or carbon rebound, effects are neutralized. Firms in the ETS pay the government for these permits. Government revenues from the ETS are in Eq. (A47) of Appendix I. We also implement fiscal neutrality in this scenario as described earlier.

3.5. Energy efficiency plus lifestyles changes in households scenario (E-HH)

Consumer behavior is affected by price and income effects, but they may also change due to technological changes (e.g., introduction of refrigerators), or due to new knowledge (e.g., awareness of environmental effects), or changes in social norms. Ho et al. (2020) discuss historical changes in consumption patterns that are not due to price or income effects, and how they might be represented in CGE models. Governments can encourage lifestyles changes through mid- and long-

[3] For detail see equations (A21), (A32), and (A46) in Appendix I.

[4] We have applied a combustion ratio of 1 for all inputs.

term strategies of awareness campaigns, but there are no direct, short-term, or certain results in comparison to previous strategies (taxes and ETS). Economic agents can also change by themselves and do so for environmental or other reasons. Therefore, comparisons with other policies should be carefully done, especially in terms of implementation. We construct two simple scenarios to illustrate the effects of changes in consumer preferences on energy use and emissions. We simulate the size of these changes that would be needed to neutralize the rebound effects.

The first consumption scenario involves a change in household energy conservation behavior (*E*-HHE), and the second scenario shifts consumption away from goods toward services (E-HHS). In each case there are two exogenous and simultaneous shocks: an energy efficiency improvement of 5% per year and changes in consumption patterns in households. In both scenarios, total available income in households remains the same as in the base case but the shares of total expenditure change. In E-HHE we reduce expenditures on petroleum refining products, electricity and gas and shift them to all other commodities proportionally to their consumption in the base case. In E-HHS we increase the consumption of services and reduce all other commodities, also proportionally to their base case consumption. Consumption share parameters (α_{it}^{c}) are modified in Eq. (A31) of Appendix I. The sum of new parameters $\alpha_{it}^{c'}$ is equal to 1:

$$C_{it} = \alpha_{it}^{c} VCC / PS_i \tag{25}$$

$$\sum_i \alpha_{it}^{c'} = 1 = \sum_i \alpha_{it}^{c} \tag{26}$$

where PS_i is the price of good i and C_i is real consumption. The size of the alternative $\alpha_{it}^{c'}$ parameters are chosen such that the rebound effects are neutralized. The different parameters means that the utility function has changed and thus welfare effects of this change cannot be directly compared. However, we can discuss the changes in GDP and emissions.

4. Results

This section includes a comparative assessment of the results obtained for the different scenarios. All scenarios include an energy efficiency improvement of 5% plus a measure that totally offsets the (energy or carbon) rebound effect triggered by this efficiency improvement. If government revenues are raised by a policy, they are recycled to keep government purchases at base case levels.

4.1. The economy-wide rebound effect for the Catalan economy

The 5% energy efficiency improvement scenario provides the economy-wide rebound effect for the Catalan economy when compared to the base case. The efficiency improvement is considered exogenous and is implemented every year of the simulation, and thus has a cumulative effect on the economy, energy use, and emissions. Recall that we define the rebound effect in terms of the actual change in energy use versus the expected change from partial equilibrium considerations.

The energy rebound effect starts at 82.88% the first year of the simulation and rises to 160.5% by the 20th year, obtaining what is known as Jevons' paradox or "backfire" (rebound higher than 100%) in the third year (see Fig. 2). The carbon rebound effect starts at 50.19% the first year and reaches 125.3% in the last year of the simulation, passing the "backfire" threshold in the eighth year. The average rebound effects for the whole period are 136.9% (ERE) and 102.55% (CRE). The growth of rebound effects tends to stabilize over time if no additional efficiency improvements are implemented. This growth in actual energy use comes in part from the higher incomes, GDP by year 20 is 0.6% higher than in the base case. The Solow growth model allows for dynamic effects, displaying rebounds from a dynamic perspective, and showing that they may be higher in the mid and long term than those estimated by static methods or models because of the growth effects from efficiency improvements. Uncontrolled rebound effects not only erode expected energy savings but are also counterproductive in the long term.

A recent literature review on economy-wide rebound effects, (Brockway et al., 2021) shows that despite the diversity of methodologies employed, assumptions used, and rebound mechanisms included, the results are broadly consistent and suggest that economy-wide rebound effects may erode more than half of the expected energy savings from improved energy efficiency. They analyzed 21 CGE modelling

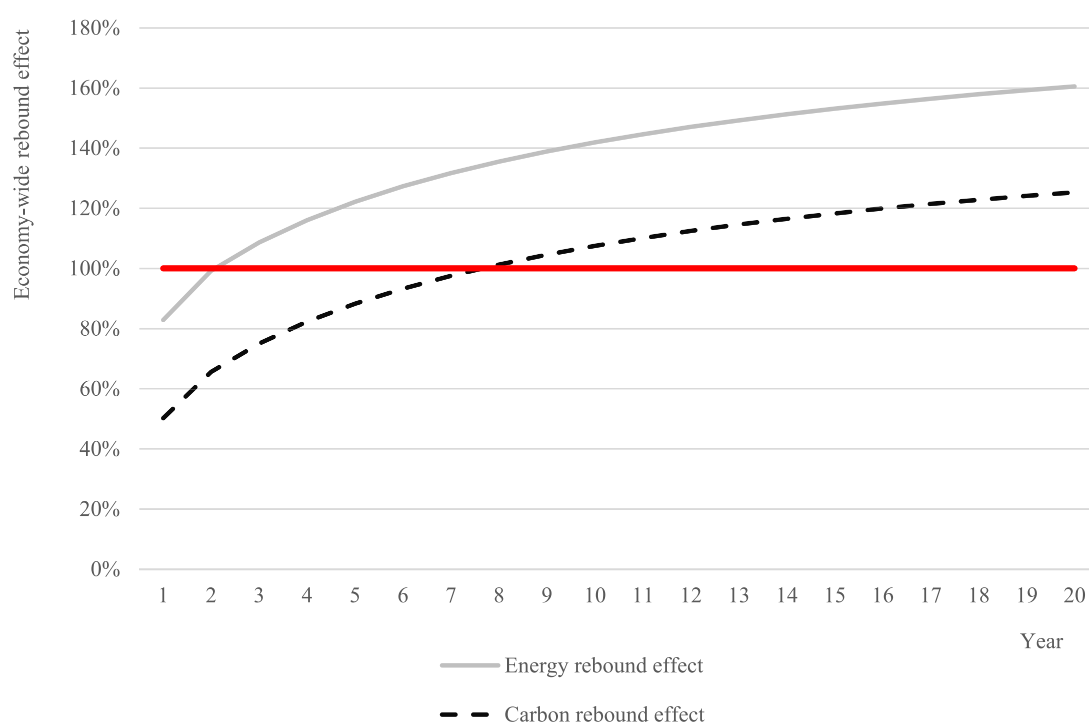

Fig. 2. The economy-wide rebound effect of the Catalan economy each year of the simulation.

studies estimating rebound effects. Seven of them also implemented a 5% energy efficiency improvement and estimated these ranges of rebounds: Hanley et al. (2009) for Scotland, 131%–134%; Anson and Turner (2009) for the UK, 39%; Guerra and Sancho (2010) for Spain, 87%; Broberg et al. (2015) for Sweden, 69%–78%; Lu et al. (2017) for China, 0.1%–42%; Lecca et al. (2014) for the UK, 64%; and Figus et al. (2016) for Scotland, 50%. So, our year 1 results for a 5% improvement for Catalonia are in line with these estimates.

We conducted two sensitivity tests of our assumptions. The first one uses a different size of energy efficiency improvement, while the second one explores costly energy efficiency improvement, instead of the costless change we have considered above: (1) In this sensitivity analysis we assume a 3% energy efficiency improvement instead of 5% to show the degree of non-linearity. With 3% improvement, the energy rebound in year one is 89.51% compared to 82.88% above, and 70.79% versus 50.19% for the carbon rebound. After 20 years of improvement at 3%, the energy rebound is 135.8% compared to 160.5%, and 115.7% versus 125.3% for the carbon rebound. That is, the slope of the rebound effect

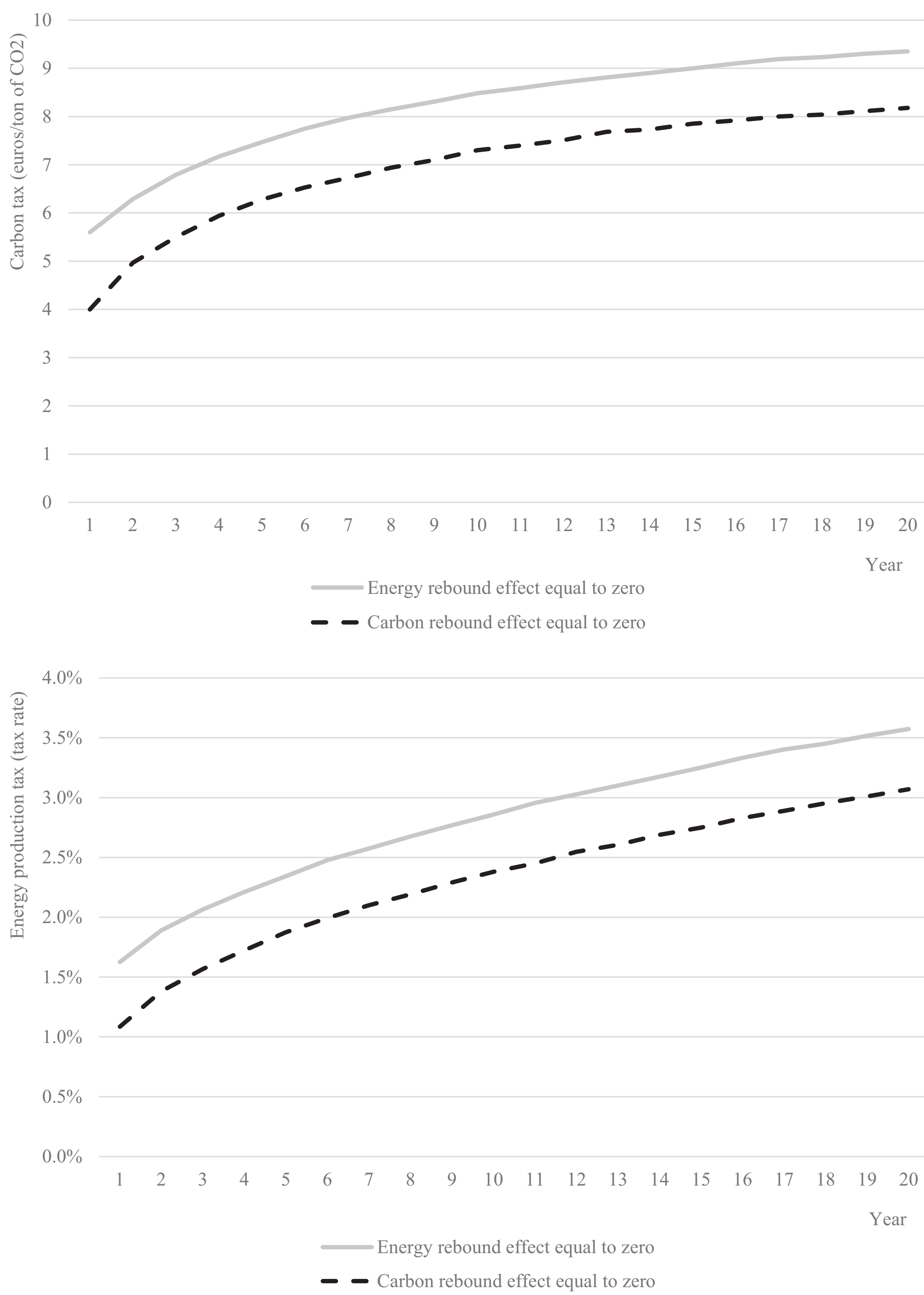

Fig. 3. Carbon and energy production taxes that totally offset energy and carbon rebound effects each year of the simulation.

over time is less steep than that in Fig. 2 for the faster efficiency improvement.

(2) In our main cases we assume that efficiency improvement is exogenous and costless to reduce the complexity of the experiment. In this sensitivity test we assume that resources have to be used every year to generate such improvements, one may think of these as R&D costs. This cost is represented by a small negative TFP shock to the production function. The net effect is equivalent to a biased technical change. We assume that the 5% efficiency improvement require R&D expenses equal to 0.2% of total unit costs annually for all industries. With this R&D cost, the energy rebound in year one is 71.89% for the energy rebound compared to 82.88% above and 39.85% versus 50.19% for the carbon rebound. Averaged over the whole period, the energy rebound is 136.0% versus 136.9% and 101.7% versus 102.6% for the carbon rebound. Since we assumed that all industries require the same R&D costs, the changes in relative prices in the R&D case are similar to the costless case, and thus the average rebound effects are very similar. This does not mean that welfare is the same, obviously GDP is lower with the cost shock, but the rebound rates are similar.

4.2. Policy scenarios

Recall that the policy scenarios include the 5% energy efficiency improvement in addition to the policy measure or preference change. In this section we detail the specific policies simulated in each scenario in terms of tax rates, target emissions, and changes in households' budgets.

4.2.1. Environmental taxation scenarios

The *E*-CT scenario imposes a carbon tax and the E-ET imposes an output tax on final energy producers. Fig. 3 shows the tax rates needed yearly to offset rebound effects. Both carbon and energy production tax rates should follow a rising path because of the cumulative effects of energy efficiency on economic growth captured by the model.

In year 1, the carbon tax would need to start at 5.6 euros/ton to compensate for the energy rebound effect and at 4 euros/ton to compensate for the carbon rebound effect. In year 20 of the simulation, the carbon tax required reaches 9.35 euros/ton to offset energy rebound and 8.18 euros/ton to offset carbon rebound effects. This means a carbon tax of between 1.12 and 1.87 euros/ton per percentage point of efficiency improvement to offset energy rebounds and between 0.8 and 1.64 euros/ton to offset carbon rebounds. Regarding the tax on energy production sectors, in year 1, the tax rate needed to offset energy rebound effects is 1.62%, and it grows until it reaches a value of 3.57% in year 20. Again, tax rates needed to compensate for carbon rebound effects are smaller with rates that range from 1.09% in year 1 to 3.07% in year 20. It represents a tax rate of between 0.33% and 0.72% per each percentage point of efficiency improvement for energy rebound effects and between 0.22% and 0.61% for carbon rebound effects. Both carbon taxes and energy production taxes rise over time but at a diminishing rate.

4.2.2. Emissions trading system

Fig. 4 shows the carbon emissions targets for the six sectors covered under the ETS needed every year to completely counteract the energy and the carbon rebound effect. In the base year 2014, total carbon emissions in Catalonia were 31.91 million tons and 12.59 million tons for primary emissions in the six ETS sectors. In the *E*-NP energy-efficiency only scenario, the six sectors emitted 13.32 million tons in 2014.

Carbon emissions targets that counteract both energy and carbon rebound effects follow a growth path, starting at 12.7 million tons in year 1 and ending at 20.55 in year 20 to offset energy rebound effects and starting at 12.88 and ending at 20.86 for carbon rebound effects. These targets are higher than base case emissions of these sectors, which are 12.59 in year 1 and 20.54 in year 20, but lower than 13.32 million tons in year 1 of the efficiency-only (E-NP) case. In year 1, there is an actual reduction of emissions in E-NP since the rebound effect is modest. To offset this modest rebound we need some sectors to cut energy use

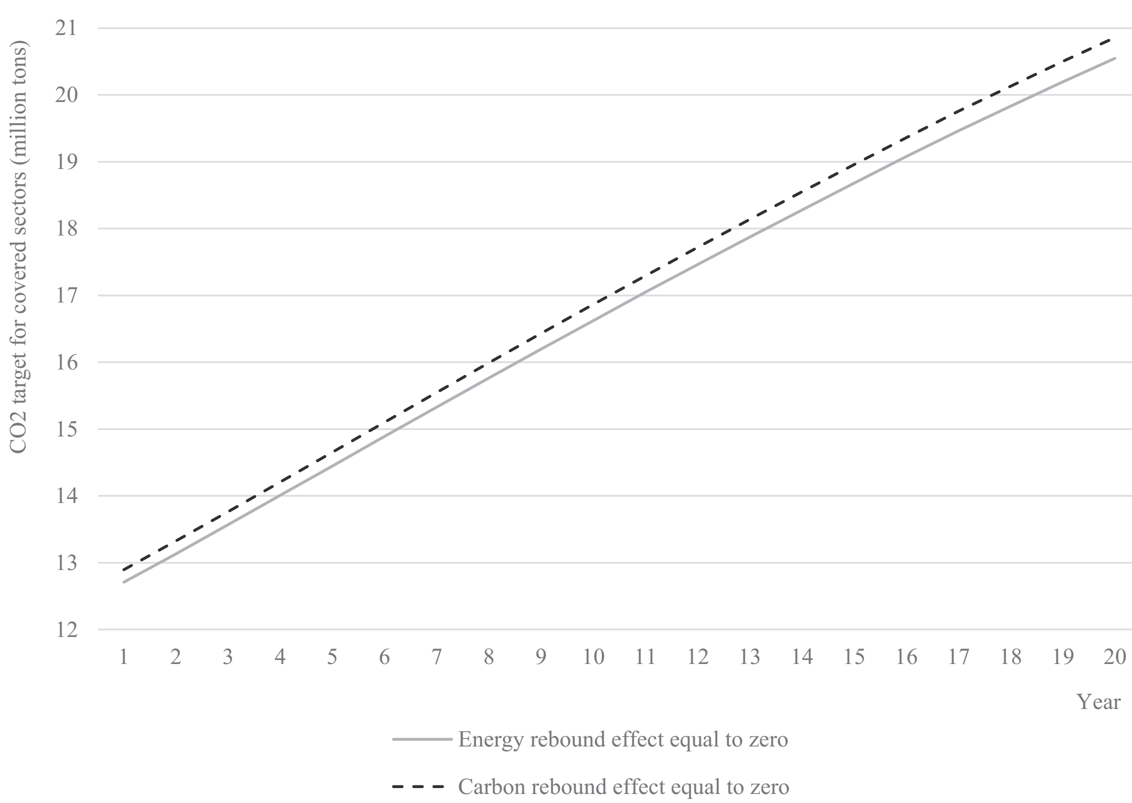

Fig. 4. Carbon emissions targets for covered sectors (million tons) that totally offset energy and carbon rebound effects each year of the simulation.

and emissions. It turns out that it is easier to let these 6 energy-intensive sectors to use more energy, lower their output prices and let the other non-ETS industries conserve their energy use. Thus, we have a carbon cap for the 6 sectors that is slightly more generous than in the base case in year 1. Over time, the rebound effects are bigger, and the cap becomes closer relative to the base case.

4.2.3. Changes in lifestyles or consumption patterns in households

In these scenarios of changing lifestyles, we modify the consumption share allocations to the different commodities. The first scenario has voluntary energy savings in households and the second has an increase of services share in household consumption.

Note: Patterns hh energy: reduction in energy consumption scenario; patterns hh services: increase in services consumption scenario. Two rebound effects considered - ERE: energy rebound effect; CRE: carbon rebound effect.

Fig. 5 presents the reduction in energy consumption needed to offset energy and carbon rebound effects, in lines marked "Patterns hh energy". This reduction is expressed as a percentage of total household expenditures, and is offset by higher expenditures on the other commodities (in proportion to their initial share in the total budget). There are two lines, one marked "ERE" for offsetting the energy rebound, and "CRE" for offsetting the carbon rebound. The percentage reductions of the total household budget reallocated to services sectors consumption from other commodities (in proportion to their initial share in the total budget) needed to offset rebounds are marked as "Pattern hh services".

Households are estimated to have to reduce their energy consumption by reallocating a sizeable 4.45% of their total consumption expenditures in year 1 and 8.55% in year 20 to offset the energy rebound effect of a 5% annual energy efficiency improvement. For the carbon rebound effect, these percentages are lower: 2.6% in year 1 and 6.55% in year 20. In the case where consumption patterns shift toward services, households would have to reallocate 1% of the total budget in year 1 and 1.9% in year 20 to compensate for the energy rebound effect and 0.58% (year 1) and 1.43% (year 20) to suppress carbon rebound effects.

4.3. Economic indicators

We now discuss the policy impacts on output and the composition of GDP (the C, I, G, X, M components). The improvement in energy efficiency (scenario *E*-NP) allows higher output from the given capital and labor inputs. This allows higher consumption, investment, and government expenditures. We do not change the parameters determining the composition of final demand, and so all C, I and G quantities rise. Alternative parallel policies could redirect some of the consumption gains, or government gains, to investment and change future GDP, however, to keep things simple we avoid imposing any other policy. In the policy scenarios that involve new government revenues, we have a parallel policy to recycle them by cutting taxes and keeping government expenditures equal to the base case. This means that G in these policy scenarios is lower than in the *E*-NP scenario, but consumption or investment could be higher. This distinction should be kept in mind when considering the simulation results that we discuss next.

In Fig. 6 we plot the change in GDP compared to the no efficiency improvement base case. The change due to the efficiency improvement only (*E*-NP) case is shown in the bold dashed line, GDP is 0.46% higher in year 1 and 0.60% higher in year 20. Despite the additional policies implemented beyond the 5% energy efficiency improvement, we observe that GDP is higher than in the base case in all the efficiency-and-policy scenarios even though it may be lower than in E-NP. That is, much of the positive economic growth effects of energy productivity improvements remain while rebounds are contained. Among the scenarios that offset energy rebound effects (Fig. 6a), the one which involve a shift of consumption patterns away from services ("patterns hh services") achieves the highest GDP variation at year 20 with a 0.8% increase in relation to the base case, followed by the energy production tax case (a 0.77% increase) and the ETS (a 0.73% increase). Regarding the scenarios that totally compensate for carbon rebound effects (Fig. 6b), the highest variations are achieved by the energy production tax scenario (with an increase of 0.78% in relation to the base case year 20), followed by the patterns hh services scenario (+0.75%) and the ETS scenario (+0.74%).

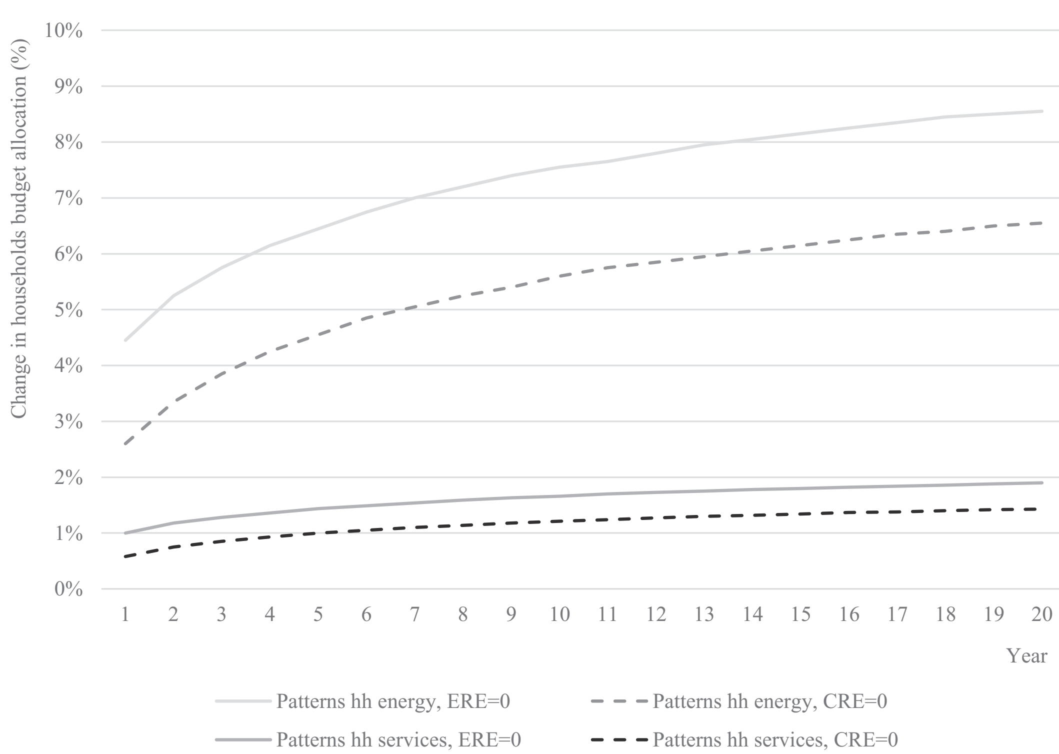

Fig. 5. Changes in households' budget allocation (%) that totally offset energy and carbon rebound effects each year of the simulation.

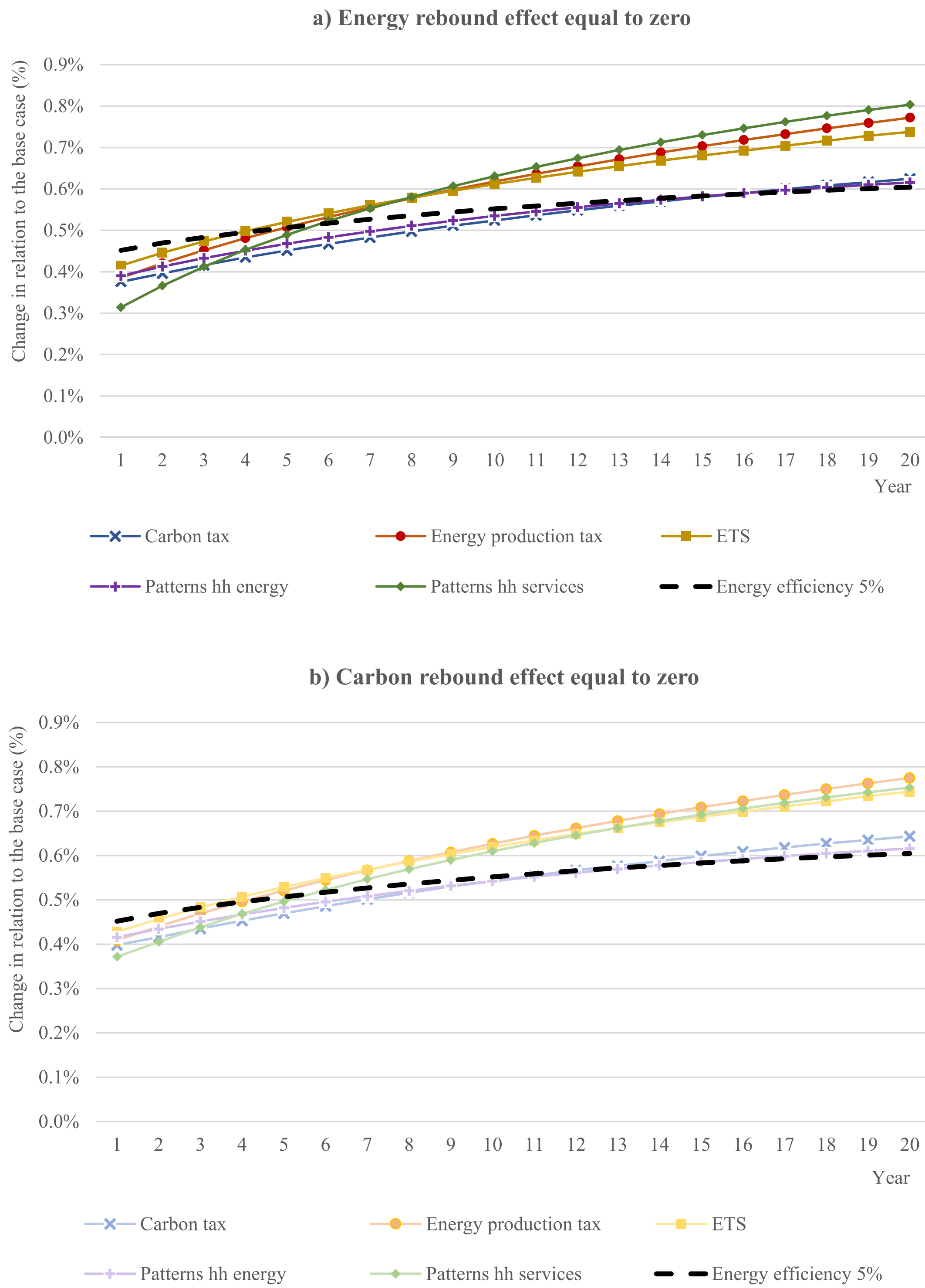

Fig. 6. GDP variation of different scenarios over the 20-year period of the simulation, in relation to the base case.
Note: Patterns HH energy: reduction in energy consumption; patterns HH services: increase in services consumption.

In all cases, economic growth at year 20 of the simulation is greater than the "energy efficiency with no policies scenario" (E-NP), which achieves a GDP increase of 0.6% in relation to the base case because of the design of these policies. These long-run GDP effects are higher than the E-NP case due to their higher investment and lower government spending in the early years compared to the efficiency-only case. However, between 4 and 15 years (depending on the scenario) are needed for these scenarios to achieve a better result than the scenario with no additional policies. Beyond offsetting carbon and rebound effects, all designed and implemented scenarios have positive economic effects compared to the base case.

If we focus on different components of GDP, we observe differences among scenarios (Fig. 7). The services consumption pattern scenarios reduce goods consumption and thus reduce imports in relation to the base case, while others slightly increase them on average. The energy consumption pattern scenarios increase exports more than the rest, on average, but less than only implementing a 5% energy efficiency improvement. In general, all final demand components for all scenarios

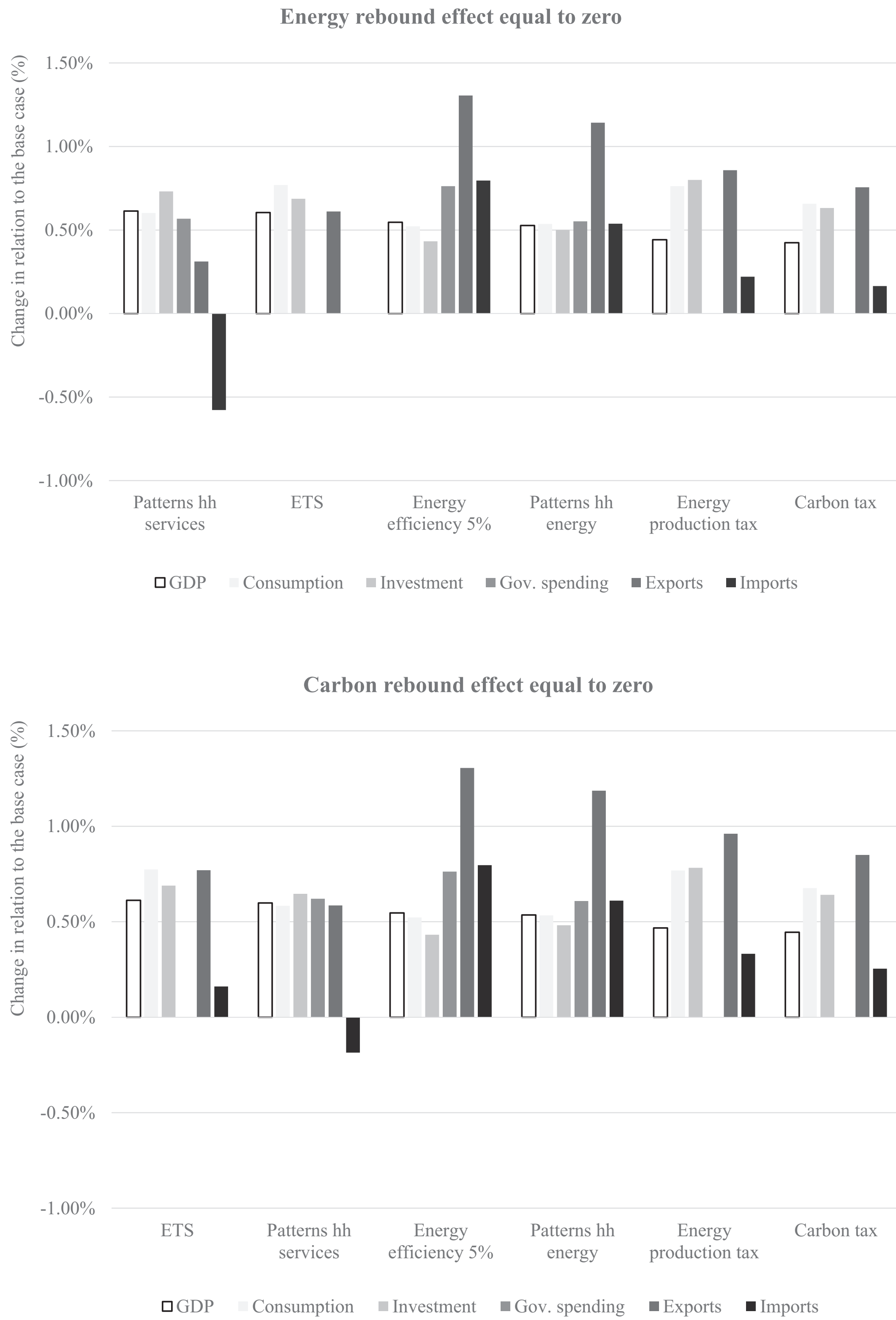

Fig. 7. Average of yearly values for the 20-year period simulation of the GDP variation (in relation to the base case) and its components for the different scenarios.

are increased in relation to the base case in all years, except for government purchases in the price policy cases (carbon tax, energy tax and ETS). In some cases, averaging over the 20-years, they increase more than in the 5% energy efficiency scenario (particularly consumption and investment of all scenarios).

Note scenarios ordered from higher to lower GDP variation in relation to the base case. Patterns HH energy: reduction in energy consumption; patterns HH services: increase in services consumption.

Finally, Figs. 8 and 9 show the production and consumer price variation of some specific sectors. We have chosen five sectors strongly related to energy and carbon emissions to see how these policies affect them individually: extraction of energy products, petroleum refining,

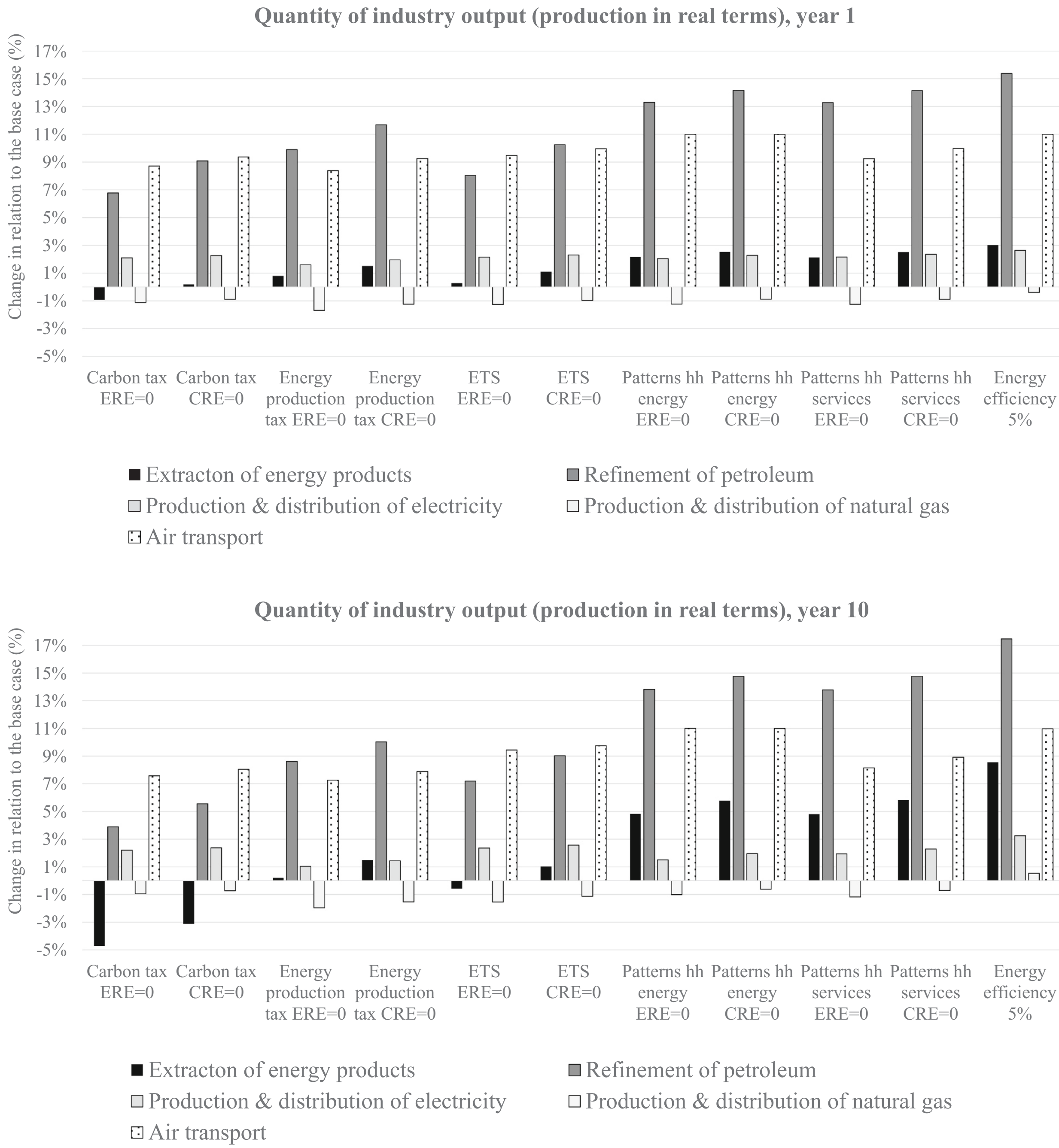

Fig. 8. Production variation of energy sectors under the different scenarios. Year 1 and year 10 of the simulation.
Note: Patterns HH energy: reduction in energy consumption; patterns HH services: increase in services consumption. ERE: energy rebound effect; CRE: carbon rebound effect.

production and distribution of electricity, production and distribution of natural gas, and air transport. We show them at years 1 and 10 to illustrate the dynamic effects.

Carbon taxes and energy production taxes directly raise the prices of fuels and thus are more effective than the other policies at containing the growth of demand and output of the energy sector coming from the improvement in efficiency, especially in the long term. Carbon taxes even reduce the extraction of energy products, and all scenarios reduce the production of natural gas in relation to the base case. The other energy sectors see an increase in their production and a reduction in final consumer prices relative to the base case, but these changes are always (algebraically) lower than the 5% energy efficiency scenario. Carbon and energy taxes, and ETS prices all induce lower energy consumption by everyone – households and producers. The shifts in the consumption patterns lower the household demand for refined oil, gas and electricity, leading to lower prices for the producers which then encourage higher use of energy by industry. We thus see a higher output of refined oil in the consumption pattern cases than in the price policy cases.

4.4. *Energy and carbon emissions indicators*

Average energy use and carbon emissions variations for the different scenarios are shown in Fig. 10. We also include energy and carbon

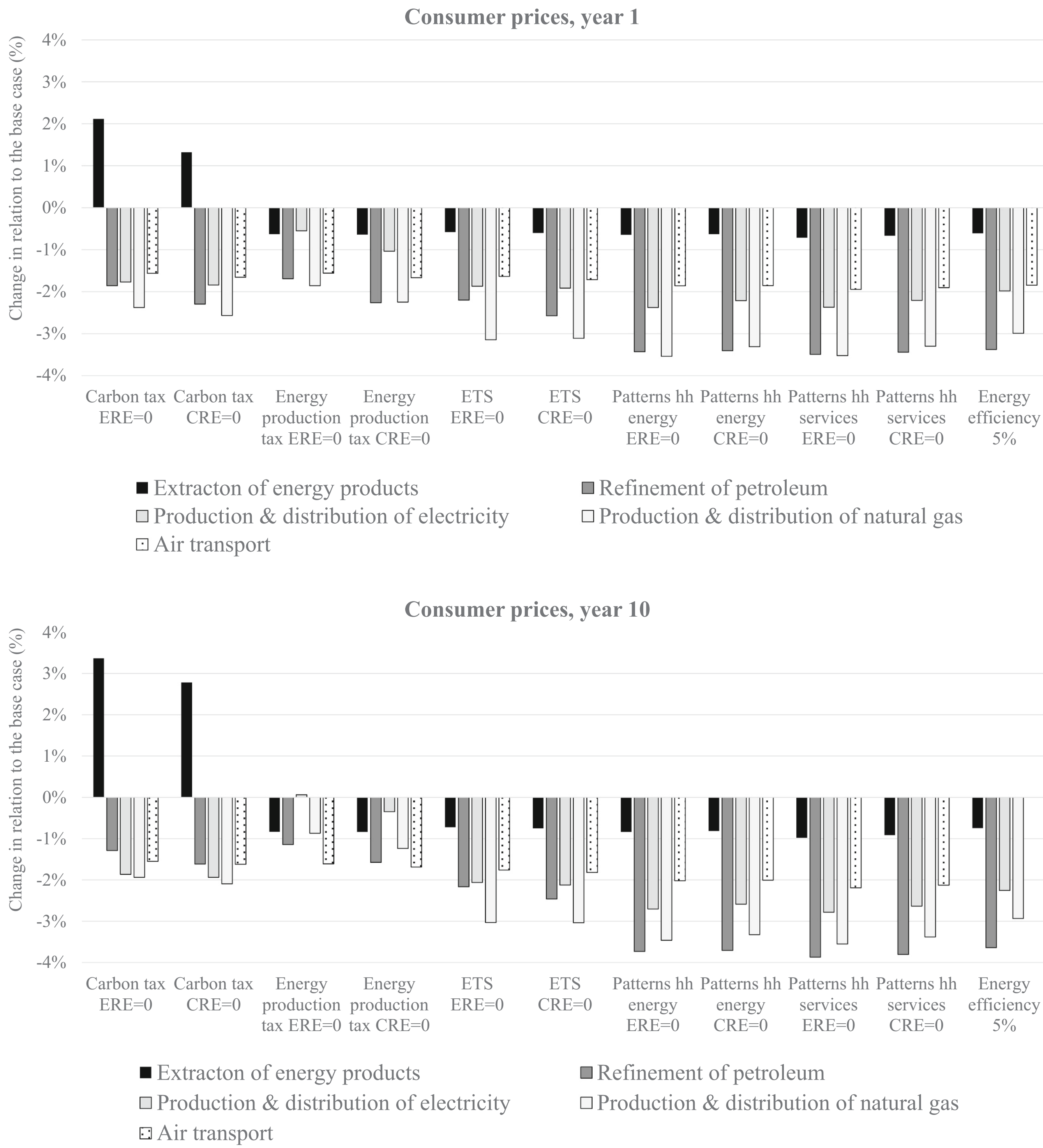

Fig. 9. Consumer price variation of energy sectors under the different scenarios. Year 1 and year 10 of the simulation.
Note: Patterns HH energy: reduction in energy consumption; patterns HH services: increase in services consumption. ERE: energy rebound effect; CRE: carbon rebound effect.

emissions intensities by dividing them by GDP. Because our objective is to suppress rebound effects, the energy use reduction is the same for all energy rebound scenarios (ERE = 0), and carbon emissions reduction is the same in the carbon rebound scenarios (CRE = 0, see Eq. (8)).

Scenarios that include changes in consumption patterns to offset energy rebound effects are the ones with the greatest reductions in carbon emissions intensity, especially the one which increases services sectors, with a 3.1% reduction in relation to the base case.

4.5. *Summary of policy effects*

The above results show that policies that change energy prices, and policies that change consumption patterns can both offset the rebound effect in energy demand from cheaper energy due to efficiency improvements. The mechanisms to achieve this offset are different; the carbon tax, energy tax and ETS raise the prices of energy and lowers the demand from all sectors, households and producers. In contrast, the

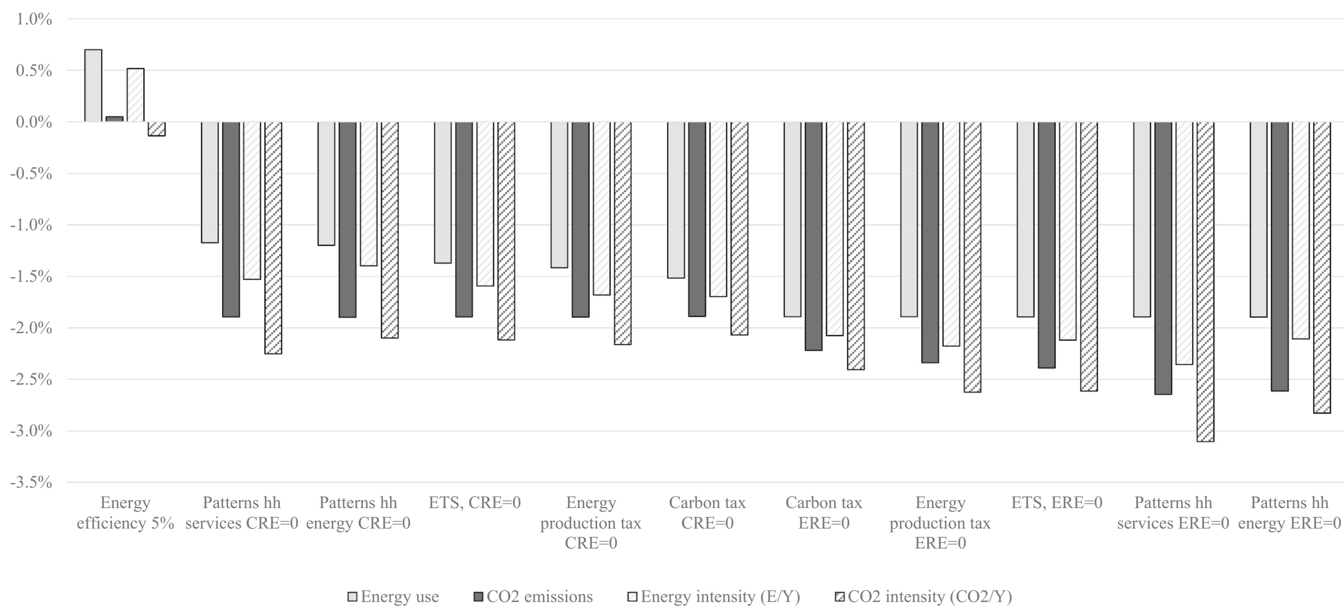

Fig. 10. Average yearly values for the 20-year period simulation of the energy use, carbon emissions, energy intensity (energy/GDP), and carbon intensity (CO_2 emissions/GDP) variations (in relation to the base case) for the different scenarios.

change in consumption patterns lead to lower energy prices which encourage the energy use by industry. We assume that factor supplies in year 1 are fixed, that is, capital and labor are not affected by any price change. Policies that impose new taxes on energy, offsetting cuts in other taxes, change relative prices and the composition of output, and thus, initial GDP is lower than in the no-policy case. Changes in consumption patterns also change relative prices and lead to a lower GDP. Differences in GDP among the policies are modest compared to the effect of the efficiency change. Besides, changes in relative prices lead to differences in distributional effects with different losses among the 64 industries.

Note scenarios ordered from higher to lower energy use variation in relation to the base case. ERE: energy rebound effect; CRE: carbon rebound effect. Patterns HH energy: reduction in energy consumption; patterns HH services: increase in services consumption.

5. Conclusions

Policy makers around the globe think that fostering energy efficiency is a useful strategy to reduce energy consumption and fight climate change. However, rebound effects reduce its effectiveness and in some cases can be counterproductive. We show how a more complex policy strategy, including several coordinated measures, would provide the expected results by offsetting potential rebounds. Different offset strategies could achieve the expected results in energy and environmental terms. The specific policy mix chosen is key in providing the desired energy, or CO_2, reductions at low costs in policy and economic terms.

Six different policy strategies or scenarios have been assessed in this research. In the first we consider only an energy efficiency improvement of 5% each year for 20 years, whereas in the other five we include an exogenous shock in addition to the same increase in energy efficiency; an additional policy that counteracts energy and carbon rebounds. We showed how energy efficiency improvement propels economic growth and increases the use of energy and carbon emissions via income and price effects. The magnitude of the change in the energy use depends on many economic factors, but the production and consumption structure of the economy and the substitution elasticities are key to explaining the rebound effects triggered by energy productivity in industries.

All policy strategies assessed can counteract both energy and carbon rebound effects at relatively low tax rates, emissions targets, or percentage changes in consumption patterns; this shows the political feasibility of these strategies, although each strategy may represent different levels of effort for different governments. For instance, it can be easier for a government, in political, institutional, social, or operational terms, to simply increase a preexisting energy production tax rate than to create a new carbon tax or an emission trading system (ETS), or to influence consumer behavior, which may require a long-term perspective and a different approach. Moreover, their design is key in providing an improvement or deterioration of macroeconomic indicators. For instance, all fiscal strategies (taxes and ETS), with revenues used in reducing other preexisting taxes, improve GDP in relation to both the base case and in the long term (year 20 of simulations) even in relation to the scenario with only an efficiency improvement of 5%. This is due to a shift away from consumption and toward investment.

Strategies oriented to changing lifestyles toward more consumption of services instead of other kinds of commodities (i.e., changing consumption patterns) may mean more implementation difficulties and a long-term perspective. They provide better economic results along with energy production taxation with recycling revenues and ETS. Changing consumption patterns to consume more services may be a more effective way to compensate for rebound effects than directly reducing energy use in households because of economy-wide general equilibrium effects. However, carbon taxation may be the most effective strategy for reducing the production of specific energy and carbon-intensive economic sectors like the extraction of energy products and petroleum refining as well as encouraging changes toward low-carbon technologies, technologies that are not captured by the kind of model used here. An emission trading system may also generate these incentives.

Efforts to offset carbon rebound effects are less than those needed for energy rebound effects because of renewable energy sources, so a transition toward these sources would allow less effort if the focus were only on climate policies rather than energy use. This approach is extensible to other non-energy resources since rebounds can be triggered by other resources susceptible to productivity improvements. This is the first study to assess and compare different policy strategies to offset rebound effects. Future research in this area to extend and improve evidence by use of different data and methodologies would be valuable, as well as applying this approach to other resources. The feasibility of these policy strategies must also be assessed from different perspectives, not just from the economic and environmental perspectives. Finally, other potential policies can be assessed within this framework, considering the effects not only on energy and carbon emissions but also on other resources and environmental impacts. This may also be extended to wider frameworks such as the environmental rebound effects proposed in sustainability sciences.

Declaration of Competing Interest

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

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Appendix I. Equations of the model

A.1. Production

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

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

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

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

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

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

$$P_{jt}^{VE} VE_{jt} = P_{jt}^{VA} VA_{jt} + PE_{jt} E_{jt} \tag{A7}$$

$$P_{jt}^{VA} VA_{jt} = P_{jt}^{KD} KD_{jt} + PL_{jt} LD_{jt} + PT_{jt} TD_{jt} \tag{A8}$$

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

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

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

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

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

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

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

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

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

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

$$PM_{jt}M_{jt} = \sum_{k \in NE} PS_{kt}A_{kjt} \; NE = \{Agri, \ldots, Otherservices\} \tag{A19}$$

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

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

$$VQC_i = PC_iQC_i = \sum_j m_{ji}^r PI_j^t QI_j \tag{A22}$$

$$PC_i = \sum_j PI_j^{t\; m_{ji}^c} \tag{A23}$$

$$m_{ji}^r = \frac{M_{ji}}{\sum_k M_{jk}} \tag{A24}$$

$$m_{ji}^c = \frac{M_{ji}}{\sum_k M_{ki}} \tag{A25}$$

A.2. Households

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

$$YL_t = \left(1 - t^{ss} - t^L\right) PL_t \; LS_t \tag{A27}$$

$$S_t^p = s_t Y_t^p = Y_t^p - VCC_t \tag{A28}$$

$$U_t = \sum_i \alpha_{it}^c logC_{it} \tag{A29}$$

$$VCC = \sum_i PS_i \; C_i \tag{A30}$$

$$C_{it} = \alpha_{it}^c VCC / PS_i \tag{A31}$$

A.3. Government

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

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

$$R_L = t^l \sum_j PL_j \; LD_j \tag{A34}$$

$$R_{Prop} = t^p \sum_j PK_jKD_j \tag{A35}$$

$$R_{YK} = t^{yk} DIV_{gross} \tag{A36}$$

$$R_{VAT} = \sum_j t_j^{vat} \left(PK_jKD_j + PL_jLD_j + P_{Landj}L_{Landj}\right) \tag{A37}$$

$$R_{Sales} = \sum_j t_j^t PO_jQI_j \tag{A38}$$

$$R_{Special} = \sum_j t_j^{sp} PO_jQI_j \tag{A39}$$

$$R_O = \sum_j t_j^o PO_j QI_j \tag{A40}$$

$$R_{SS} = t^{ss} \sum_j PL_j \, LD_j \tag{A41}$$

$$R_{Tariff} = \sum_i t_i^m \, e \, PM_i M_i \tag{A42}$$

$$TAXN_{HH} = g_{NHH} \, GDP \tag{A43}$$

$$TAXN_{ENT} = G_{ENT} \, GDP \tag{A44}$$

$$R_{subsidy} = \sum_j t_j^s PO_j QI_j \tag{A45}$$

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

$$R_{ETS} = \sum_{i \in I_{COM}^{CO_2}} \sum_{j \in Covered} t_{ij}^{xCO_2} \rho_{ij}^{cmb} A_{ij} + \sum_{j \in Covered} t_{elec,j}^{xCO_2} A_{elec,j} + t_j^{xpu} QI_j \tag{A47}$$

$$Expend = VGG + G_{INV} + G_{IR} + G_{SS} + G_{INT} + G_{Transf} + G_{CTS} \tag{A48}$$

$$VGG = GG \, PGG \tag{A49}$$

$$G_{Transf} = \gamma^{tr} PL_t POP_t \tag{A50}$$

$$PS_i G_i = \alpha_i^G VGG \tag{A51}$$

$$\Delta G_t = Expend_t - Rev_t \tag{A52}$$

A.4. Capital

$$K_{jt} = (1 - \delta) K_{jt-1} + I_{jt} \tag{A53}$$

$$K_{jt} = K_j(PK_1, \ldots, PK_n) \tag{A54}$$

$$\sum_j Profits_j + \sum_j PK_j KD_j + \sum_j PT_j TD_j = R_K + RE_j + DIV \tag{A55}$$

$$PI_{jt} I_{jt} = \alpha_{jt}^I II_t \tag{A56}$$

A.5. Foreign sector

$$DS_i = A_0 \left[\alpha^d DC_i^{\rho} + \alpha^m M_i^{\rho} \right]^{1/\rho} \tag{A57}$$

$$PS_i = \frac{1}{A_0} \left[\alpha^{d\sigma} PD_i^{1-\sigma} + \alpha^{m\sigma} M_i^{1-\sigma} \right]^{1/1-\sigma} \tag{A58}$$

$$VQS_i = PS_i DS_i = PD_i DC_i + PM_i M_i \tag{A59}$$

$$PM_i = e\left(1 + t_i^m + t_i^{vat} + t_i^{mv}\right) PM_i^* + t_i^{mc} \tag{A60}$$

$$QC_{it} = k_{it}^x \left[\alpha_{it}^x X_{it}^{\frac{\sigma_i^e - 1}{\sigma_i^e}} + \left(1 - \alpha_{it}^x\right) DC_{it}^{\frac{\sigma_i^e - 1}{\sigma_i^e}} \right]^{\frac{\sigma_i^e}{\sigma_i^e - 1}} \tag{A61}$$

$$PX_{it} = e_t \left(1 + s_{it}^e\right) PE_{it}^* \tag{A62}$$

$$X_{it} = DC_{it} \left[\frac{1 - \alpha_{it}^x}{\alpha_{it}^x} \frac{PD_{it}}{PX_{it}} \right]^{\sigma_i^e} \tag{A63}$$

$$PC_{it} QC_{it} = PD_{it} DC_{it} + PX_{it} X_{it} \tag{A64}$$

$$CA = \sum_i \frac{PX_i X_i}{(1+s_i^e)} - \sum_i ePM_i^* M_i - NFY - G_{IR} + R_{Transfer} \tag{A65}$$

A.6. Markets

$$DS_i = \sum_j A_{ij} + C_i + G_i + I_i \tag{A66}$$

$$\sum_j \psi_{jt}^L LD_{jt} = LS_t \tag{A67}$$

$$KD_{jt} = \sum_j \psi_{jt}^K K_{jt} \tag{A68}$$

$$TD_j = T_j \tag{A69}$$

$$S^P + RE + G_{INV} = II + \Delta G + CA \tag{A70}$$

A.7. Energy and CO_2 emissions

$$EN = \sum_i e_i q_i (QI_i - X_i) + \sum_i e_i q_i M_i \tag{A71}$$

$$CO_2 = \sum_i c_i e_i q_i (QI_i - X_i) + \sum_i c_i e_i q_i M_i \tag{A72}$$

A.8. Variables and parameters (in order of appearance):

PI_j price of output of industry *j*.
QI_j quantity of output of industry *j*.
P_j^{KD} price of capital.
KD_j quantity of capital.
PL_j price of labor.
LD_j quantity of labor.
PT_j price of land.
TD_j quantity of land.
PB_{ij} price of intermediate input *i* to industry *j*.
A_{ij} quantity of intermediate input *i* to industry *j*.
k_{jt}^{QI} parameter of the QI cost function set at the calibration process.
g_{it} TFP of industry *i* at period *t*.
$\alpha_{M_{jt}}$ share for all material inputs into industry *i* at period *t*
$1/\sigma_{jt}^{QI}$ elasticity of substitution between VE and PM composites (see Fig. 1)
t_j^{res} *ad-valorem* resource taxes
t_j^{x} *ad valorem* externality taxes
t_j^{c} unitary carbon taxes
t_j^{s} subsidies to production
t_j^{t} sales taxes
t_j^{sp} special taxes (which includes special taxes on alcohol, tobacco, hydrocarbons, electricity, and retail hydrocarbons)
t_j^{o} other taxes
VQC_i value of domestic commodity *i*
PC_i price of this domestic commodity
QC_i quantity of domestic commodity
m_{ji}^{r} row shares of use table
m_{ji}^{c} column shares of supply table
Y^p aggregate is private income
YL aggregate labor income
DIV dividend income
G_I interests received from public debt
$G_{transfer}$ transfers from the government
$R_{transfer}$ incomes from the rest of the world
FEE nontax fees
t^{ss} aggregate social security tax rate on labor

t^L labor tax rate
PL wages
LS aggregate supply of labor
VCC_t consumption
S_t^p savings
s_t savings rate
PS_i supply prices of commodities
Y^p aggregate private income
U_t households' utility
C_{it} consumption of commodities
α_{it}^c consumption shares
Rev total government revenues
R_K direct taxes on capital revenues
R_L taxes on labor revenues
R_{Prop} taxes on property revenues
R_{YK} taxes on dividends revenues
R_{VAT} indirect taxes on production and commodities revenues
R_{Sales} taxes on sales revenues
$R_{Special}$ special taxes revenues: alcohol, tobacco, hydrocarbons, electricity, and retail hydrocarbons
R_O other taxes revenues
R_{SS} social security contributions revenues
R_{Tariff} tariffs revenues
$TAXN_{HH}$ nontax revenues from households
$TAXN_{ENT}$ nontax revenues from firms
$R_{subsidy}$ production subsidies
R_c revenues from CO_2 emissions tax
R_{ETS} ETS revenues
t_j^{vat} VAT tax rate
e exchange rate
t_i^m imports tax rate
t_i^{mv} *ad valorem* carbon tax on imports
t_j^{mc} unit carbon tax on imports
g_{NHH} coefficient for nontax payments by households to government
G_{ENT} coefficient for nontax payments by enterprises to government
GDP gross domestic product
$t_{ij}^{xCO_2}$ carbon prices paid by industries covered by the ETS for hydrocarbons and exempted for others
$t_{elec,\,j}^{xCO_2}$ carbon prices paid by industries covered by the ETS for electricity and exempted for others
t_j^{xpu} unitary carbon prices paid by industries covered by the ETS and exempted for others
A_{ij} quantity of intermediate input i to industry j
VGG value of purchased of commodities by government
G_{INV} government investments
G_{IR} government transfers to rest of world
G_{SS} social contributions to households
G_{INT} interests paid for public debt
G_{Transf} other transfers to household
G_{CTS} value of freely allocated permits paid by "covered" industries in energy/emissions cap-and-trade system
GG real government purchases
PGG price of government purchases
γ^{tr} parameter for transfers
PL_t wage rate
POP_t population
α_i^G individual shares of government purchases
ΔG_t government deficit
$Expend_t$ government expenditures
Rev_t government revenues
K_{jt} capital stock
δ depreciation rate
I_{jt} investments
R_K corporate income taxes
RE_j retained earnings
DIV dividends
α_{jt}^I industry shares
II_t total investment
$PI_{jt}I_{jt}$ sectorial value of investments
DS_i total domestic supply
DC_i domestically produced commodities

M_i imported commodities
α^d shares of domestic commodities
α^m shares of imported commodities
$\sigma = 1/(1-\rho)$ elasticity of substitution between imported and domestic commodities
PM_i* prices at foreign currency
e exchange rates
DC_{it} domestic consumption
X_{it} exports
σ_i^e elasticity of transformation
α_{it}^x shares of exported commodities
s_{it}^e export subsidies
CA current account balance
NFY value of net capital incomes transferred abroad
G_{IR} net government payments transferred abroad
$R_{Transfer}$ net transfers from rest of world to households
ψ_{jt}^L wage distribution coefficients
ψ_{jt}^K capital rental price distribution coefficients
q_i quantity coefficients (tons/euro) for energy source i, or m3/euro for gas
e_i energy coefficients (joules/tones) for source i, or joules/m3 for natural gas
c_i emission coefficients (tons of CO_2/joule) for source i
EN total energy used by economic system
CO_2 total carbon emissions

A.9. Values of elasticities

Non-energy intermediate inputs: σ_{jt}= 1 (Catalan SAM)
VA composite: σ_{jt}^{VA}= 0.2–1.68 (Hertel et al., 2014)
Energy intermediate inputs composite: σ_{jt}^E= 0.5 (Ross, 2007)
VE composite: σ_{jt}^{VE}= 0.5 (Ross, 2007)
QI composite: σ_{jt}^{QI}= 0.15 (Cao et al., 2019)
Domestic and imported goods composite (CES): σ_i^m= 0.571–2.020 (Aspalter, 2016; Németh et al., 2011)
Domestic and exported goods composite (CET): σ_i^e= -1.926 (Imbs and Mejean, 2010)

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