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Targeting energy savings? Better on primary than final energy and less on intensity metrics

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ABSTRACT

Energy efficiency is a critical issue in public policies, as it is the key to decoupling economic growth and energy use. These objectives are becoming even more relevant to addressing the energy crisis and the new geopolitical scenarios delivered by the Ukraine war. Although several papers have analyzed energy efficiency goals, this paper focuses on energy savings targets, which represent the main efficiency metric for the European Union. This paper fills a gap in literature by analyzing the economic and environmental impacts of attaining energy efficiency targets through an energy fiscal policy, simulated by a hybrid computable general equilibrium model with technological detail. Six scenarios are defined for energy savings in primary/final energy consumption of fossil-fueled/all energy products, using Portugal as a case study. Relevant insights for policy makers from the simulated scenarios include: (i) achieving energy saving targets by alternative means, i.e., directed at primary or final energy consumption, provide heterogeneous impacts on the efficiency of the energy system and GDP, and some unexpected and undesirable outcomes concerning environmental impacts; (ii) a relatively lower taxation of all energy products deliver larger and more distorting impacts on electricity generation than higher taxes on fossil fuels only (a counterintuitive result), (iii) policies aiming to reduce primary energy instead of final energy provide the best outcomes (further increases in the efficiency of the energy system with smoother economic impacts), thereby pointing against the European Energy Taxation directive principle that taxation should be levied on final products, regardless of inputs used in their production and (iv) and targets should not be set up based on energy intensity indicators. Hence, it is shown that the size of the trade-off between economic and environmental concerns depends on where (primary or final energy consumption) and what (fossil or all energy products) energy savings are targeted.

1. Introduction

The energy sector represents around two-thirds of total anthropogenic greenhouse gas (GHG) emissions (IEA, 2021), which are recognized as the main factor causing climate change (IPCC, 2013). Given the crucial role of energy in modern societies and the multiple impacts associated with energy consumption (such as resource depletion, pollution, climate change, and energy and economic security), energy efficiency emerges as the key to prevent the increase in energy consumption without sacrificing the use of energy services and economic progress (i.e. to decouple economic growth and energy use).[1] Even though a rebound effect[2] is likely to occur, increased efficiency may reduce energy consumption – thus catalysing a series of beneficial effects on the environment, economy and society (e.g. decreasing GHG

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[1] "Energy efficiency is the most cost-effective way of reducing energy consumption while maintaining an equivalent level of economic activity. Improving energy efficiency also addresses the key energy challenges of climate change, energy security and competitiveness" (EC, 2008; p.2).

[2] The rebound effect occurs because energy efficiency may lead to a reduction in relative energy prices. Such reduction may have income and substitution effects that stimulate energy demand that, therefore, may reduce the initial potential energy-savings from energy efficiency improvements (Broberg et al., 2015; Yu et al., 2015). Rebound effect thus implies that a direct causal relationship between efficiency improvements and demand reductions does not exist.

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emissions, reducing production costs, improving human health; EC, 2014a). Energy efficiency thus has a key role in decarbonizing the economy, improving energy security and fostering economic activity.

In the European Union (EU), energy efficiency is a priority political action towards a low-carbon economy as well as a critical factor in the strategies for energy and climate action (EC, 2019). It was one of the three pillars (along with GHG emissions and Renewable Energy Sources [RES]) of the 2020 Energy and Climate Package (EU, 2009a, 2009b, 2009c). Presently, it is embodied in the 2030 Climate & Energy Framework (EC, 2014b), which aims achieving at least 32.5% improvement in energy efficiency by 2030 as compared to a business-as-usual scenario. In the clean energy transition required to achieve climate neutrality by 2050, energy efficiency is among the priorities as underlined in EU Green Deal (EC, 2019) and consequently in 'Fit for 55' package (EC, 2021a). In particular, as an intermediate step towards climate neutrality, the EU has raised its 2030 emission mitigation goal to at least 55% (from 1990 levels) and the target for energy efficiency is proposed to follow an increase from 32.5% to 36% for final, and 39% for primary energy consumption (EU, 2021). Furthermore, in the present context of Russia/Ukraine conflict, energy efficiency reinforces its key role in curbing EU energy dependency from the exterior.

While energy efficiency is usually measured in energy intensity or its inverse (energy productivity), the energy efficiency targets established by the EU energy and climate policies are expressed in terms of energy savings in absolute terms. That is, they are not measured in relation to any indicator of economic activity, such as Gross Domestic Product (GDP), or in physical terms, such as the energy requirements per unit of output. Hence, within the EU, achieving a 32.5% reduction in energy consumption implies that energy consumption cannot exceed 1273 Million tonnes of oil equivalent (Mtoe) of primary energy and/or 956 Mtoe of final energy (EU, 2018). It should be noted that the EU target for energy savings does not imply any binding target at the country level; instead, each Member State sets its indicative contributions provided that the EU global target is attained (EU, 2018). Accordingly, Portugal set out a target of a 35% reduction in energy consumption, meaning that primary and final energy consumption can be no more than 21.5 Mtoe and 14.4 Mtoe, respectively, by 2030 (RCM 53/2020). We follow in this paper the EU terminology and, thus, the concept of 'energy efficiency' refers to reductions in energy consumption.

Looking back at the 2020 targets, preliminary data points towards that the EU achieved the target for energy efficiency. Still, despite energy efficiency improvements existed, attaining this target was mainly owed to the several strong restrictions to the functioning of the economy and to private lives imposed by the COVID-19 pandemic situation faced in 2020, which decreased energy consumption considerably (EEA, 2021). Likewise, for Portugal, provisional data indicates that national target for primary energy consumption was achieved (DGEG, 2022). Nevertheless, once again, the pandemic situation provoked a 7.2% and 7.5% decrease in final and primary energy consumption in 2020 compared to 2019, respectively (APA, 2021), suggesting that if this shock did not exist, the country would not have succeeded in this domain.[3] Both the EU and the Portuguese performances show there is still a long way to go regarding energy savings. This justifies the impact assessment of alternative policies that foster energy savings and thus contribute to decoupling economic growth and energy use. In this regard, it should be noted that the EU has already highlighted that Member States aggregate contribution to meeting the 32.5% target for 2030, as portrayed in the draft National Energy and Climate Plans, fall short 2.8 p.p. and 3.1 p.p., if considering primary or final energy consumption, respectively and this gap will further affect the efforts needed to reach more ambitious energy efficiency targets (EC, 2020).

Often, energy efficiency policies are implemented via nonmarket-based or regulatory instruments that mainly influence behavior and awareness, such as energy standards, labeling or information and education, for example. An estimation of the energy savings induced by energy efficiency policies in the EU between 1990 and 2013 carried out in Bertoldi and Mosconi (2020), shows that the policies adopted were particularly effective in the industrial sector, whilst in the services' sector their effectiveness was compromised by the market fragmentation, among other factors. However, the impact of other types of policies, notably taxes, could not be derived, a caveat that the authors recognize that limits the policy implications to be inferred from their study.

For all the above reasons, energy efficiency is a recurrent subject in literature, and computable general equilibrium (CGE) models are increasingly applied (Babatunde et al., 2017). Most of the studies focus on rebound effects and on the extent to which they compromise the effectiveness of energy efficiency policies (e.g. Freire-González, 2020; Böhringer and Rivers, 2021; Du et al., 2020; Khoshkalam and Sayadi, 2020; Wei and Liu, 2017; Koesler et al., 2016). Some studies quantify the impact of energy efficiency improvements on the growth and structure of the economy, crucial metrics for policy makers. Examples include Bataille and Melton, 2017; Figus et al., 2017; Wu et al., 2019; Liu et al., 2019, who applied CGE models to assess the impacts of energy efficiency improvements on economic growth in, respectively, Canada, the UK, Taiwan and eight world regions. These broadly concluded that energy efficiency improvements lead to an increase in GDP and employment resulting from the increase in output in almost all non-energy sectors, as well as to an increase in households purchasing power.

Existing literature shows that CGE models are mostly used to assess the economic impacts of taxes to reduce CO_2 emissions (e.g. Antosiewicz et al., 2022; Xu and Wei, 2022; Fu et al., 2021; Shi et al., 2019; Lin and Jia, 2018; Liu and Lu, 2015) rather than to assess the economic impacts of meeting energy saving targets. Indeed, carbon taxes have received much more attention in literature than resource (e.g., energy) taxes, making carbon tax research considerably more abundant than energy tax's (Lin and Jia, 2020). Still, some studies focus on the economic impacts of energy fiscal policies and broadly show that energy taxes lead to energy savings and emission reductions but also lead to decreases in GDP due to reduced sector activity and production levels. Recent examples of literature investigating the economic impacts of energy tax policies mainly focus on fossil energy, and include Nong (2018), Lin and Jia (2019 and 2020), Hu et al. (2021), Peng et al. (2019), whereas Freire-González and Puig-Ventosa (2019) focus on electricity but disaggregates fossil and renewable generation. Nong (2018) simulates the impacts of rising coal and petroleum taxes in Vietnam, thus leaving behind natural gas, and not disaggregating the electricity sector (e.g. renewable versus fossil-fueled power generation). Lin and Jia (2019) investigated the impacts of alternative energy fiscal policies on fossil energy industries, regarding different tax rates and tax types (specific vs. ad valorem). Results show that ad valorem taxes lead to the most negative economic impacts (on GDP, prices, energy output), but to the most positive ones regarding emissions and energy efficiency. Lin and Jia (2020) and Hu et al. (2021) compare the impacts of energy taxes on fossils and carbon taxes in China and came up with contradictory conclusions: the former conclude that energy taxes lead to smaller impacts on GDP than carbon taxes and therefore are preferable, whereas the latter conclude the opposite. Differently, Freire-González and Puig-Ventosa (2019) investigate the economic and environmental impacts of taxes on electricity in Spain splitting the power sector into fossil and renewable generation. They compare such scenario with the undifferentiated taxation of electricity, and simulate alternative growth rates for renewables in power generation. The authors conclude that, in a revenue neutral framework, taxation of fossil-fueled electricity broadly leads to more favorable economic and environmental impacts than taxation of

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[3] By 2020, Portugal attained a 32.3% reduction in GHG emissions as compared to 2005 and a 33.9% share of RES in final energy consumption (APA, 2021), thereby achieving the national targets on these subjects (18% to 23% reduction in GHG emissions and a 31% share of RES in final energy consumption (EU, 2009a, 2009b, 2009c).

all electricity, what differs from practice in several countries, where electricity taxation disregards its source. Within this same topic, Mahmood and Marpaung, 2014 and Peng et al., 2019 show that combining energy fiscal policies and energy efficiency improvements results in a growth in GDP as well as larger reductions in energy consumption and associated GHG emissions than only fiscal policies. The latter authors simulated the impacts of an energy excise tax on energy goods in five energy sectors in the Chinese province of Jiangsu and further explored the rebound effect of energy efficiency improvements. Results point towards beneficial effects of the tax on energy savings, but to negative economic impacts in terms of GDP and welfare. Results also show that the rebound effect strongly depends on whether efficiency promotion is costly or not, with costly alternatives bringing better results in terms of energy savings.

Despite existing literature shows that CGE models are mostly used to assess the economic impacts of taxes to reduce CO_2 emissions rather than to assess the economic impacts of meeting energy saving targets, fiscal measures have proved to be effective in lowering energy intensity, e.g., in a group of high-income countries, in which Portugal is included (Azhgaliyeva et al., 2020). Furthermore, economic instruments like taxes affect the cost-effectiveness of investments in energy efficiency and thereby stimulate innovation in energy technologies (García-Quevedo and Jové-Llopis, 2021). As stated by Linares and Labandeira (2010), energy efficiency policies that effectively reduce energy demand always imply a cost, even though their benefits may be compensatory, notably in terms of environmental benefits or energy security. Moreover, the authors argue that taxes provide better results than non-market policies (such as standards) to achieve reductions in energy demand when energy prices are low and therefore do not incentivize investments in energy efficiency.

This paper contributes to the literature in that it departs from energy savings targets to design alternative energy consumption taxation policies that ensure their compliance- in particular, by comparing primary versus final energy taxation as alternative means to achieve energy savings targets. Selecting one policy or the other has completely different consequences, a question that is absent of the energy and climate debate despite the centrality of energy savings. This issue has not been explored in literature thus representing the main contribution of this paper. This topic becomes even more important considering that the proposal for the revision of the Energy Taxation Directive (EC, 2021b) emphasizes the importance of taxing fuels according to energy content and environmental performance rather than to volume, but completely disregards the distinction between primary and final energy taxation. In this context, the objective of this paper is to perform an exploratory scenario simulation exercise of a milder and a more stringent taxation of primary and final energy consumption to ultimately achieve energy efficiency targets (measured as energy saving targets, as defined by EU climate policies). Thus, the paper does not simulate cost functions associated with energy-saving measures on different sectors, according to engineering cost estimates or provided by stakeholders, because they are beset by many uncertainties (e.g. the efficiency paradox, which is associated with the lack of information related to the adoption of technologies that are apparently cost-free for firms). Accordingly, instead of imposing external cost estimates for energy savings targets into the CGE, the paper simulates the lower and more efficient cost for energy savings by means of a tax tool for simulation purposes, following the static and dynamic efficiency rationale attached to environmental taxes. To this end, a hybrid static CGE model for a small open economy is developed, comprising 31 production sectors, a technological disaggregation of the electricity production sector, and labor market imperfections. A case study is provided for Portugal, which aims to meet the energy efficiency targets established within the EU and Portuguese energy and climate policies for 2030. Despite its decline in the last decades, in 2020, 65.3% of the energy in Portugal's economy is still dependent of imports, vis-à-vis the EU27 average of 57.5% (Eurostat, 2022a). This makes energy efficiency a pivotal strategy to reduce the country's energy dependency. Electrification has been pointed out as a driver to promote energy efficiency, and, in this sense, Portugal has privileged conditions due to its high renewable potential. This is reflected in the country 's 2020 share of energy from renewable sources – 34.0% (the fourth highest value in EU27), vastly supported by more than 58% of renewable electricity (Eurostat, 2022). As a consequence, the policy implications delivered by this study will be rather conservative for generalization to the EU, i.e., they show more moderate impacts than might be the case in countries whose energy mix has a larger share of fossil energy. This occurs because the gains in efficiency when focusing on reducing primary energy instead of final energy will be greater the lower the penetration of renewables, as explained in the paper. Hence, our results show the lower bounds of the economic impacts of the simulated energy fiscal policies.

All these conditions make Portugal a relevant case study to understand how energy fiscal policies may promote effective energy savings and how these affect the national economy and energy system. Not only it delivers useful insights to regions under close circumstances but also may work as a baseline for countries whose energy mix differs from the Portuguese.

Our findings contribute to the literature by providing some general lessons that are of political and scientific relevance at the international scale by contrasting the impacts of different forms of taxing energy consumption - primary or final, only fossil or indiscriminately - to attain aggregate energy savings and, therefore, energy and climate policy goals. In particular, achieving energy saving targets by alternative means, i.e. directed at primary or final energy consumption, points towards: (i) heterogeneous impacts on GDP and on the efficiency of the energy system that, in particular may call into question the Energy Taxation Directive principle that taxation should be levied on final products, regardless of inputs used in their production, (ii) some unexpected and undesirable outcomes with regard to the environmental impacts; and (iii) larger and more distorting impacts on electrical generation sector arising from a lower savings objective for all energy products (i.e., the aggregate saving objective spread between all energies), as compared to those resulting from a higher savings objective for fossil fuels only, which is counterintuitive (larger tax basis should deliver lower impacts). The paper thus provides valuable lessons for policy-makers in charge of national energy efficiency policy as not only primary energy targets emerge as the most cost-effective policy (i.e. value-added generation versus energy savings), but also targets based on energy intensity indicators appear to be misleading.

The remainder of this paper is organized as follows. Section 2 describes the CGE model and data. Section 3 describes the assessed scenarios. Section 4 presents and discusses the impacts of simulated policies. Section 5 presents the main policy implications and Section 6 concludes.

2. Model and data

A hybrid, static (i.e. that shows the full change in the economy as a reaction to a policy shock without showing the intermediate steps or transition between the initial and final stage) CGE model for a small open economy is developed, building on the one developed by Labandeira et al. (2009). The model is extended with labor market imperfections and the technological disaggregation of the electricity production sector. The model has been programmed within General Algebraic Modelling System (GAMS; Rosenthal, 2012), using the Mathematical Programming System for General Equilibrium (MPSGE) subsystem (Rutherford, 1999) and solved using the PATH solver (a non-linear solver that finds the optimal solution based on the mixed complementarity problem approach[4] (Dirkse and Ferris, 1995). The model comprises 31 production sectors (4 energy sectors and 27 non-energy sectors) and 3 institutional sectors (private sector, public sector and foreign sector). Primary production factors are capital and labor[5]. Considering that this paper focus on the impacts of alternative ways to achieve energy saving targets, rather than on the between the pre- and post-policy equilibriums, this static modelling approach perfectly suits our purpose on the light of the principle of parsimony: to contribute to a better scientific-policy interface by using no more “things” than necessary, with “things” in this research referring to the methodology.

2.1. Production activities

Producer behavior is based on the profit maximization principle, such that in each sector a representative firm maximizes profits subject to a constant returns to scale technology – characterized by a succession of nested constant elasticity of substitution (CES) production functions combining intermediate inputs and production factors (Fig. 1). Produced goods and services are, in turn, split between the domestic and export markets according to a constant elasticity of transformation function (see also Section 2.3. Foreign sector).

The model includes a bottom-up representation of the Portuguese power sector, which is represented by a set of eight discrete technologies[6] that, together, provide the homogeneous electricity commodity. Each technology is described by a CES function combining different inputs: primary factors (labor and capital), materials and energy resources (Fig. 2). This approach follows several examples in literature, such as Cai and Arora (2015), Proença and St. Aubyn (2013), and Wing (2008).

2.2. Domestic final consumers

Household behavior follows the welfare maximization principle, such that a representative consumer maximizes utility (welfare) subject to a budget constraint. Consumption is captured through a succession of nested functions that combine, at the top level, demand for leisure and a composite good (made up of savings and consumption of goods and services) according to a CES function (Fig. 3). At the second level, savings trade-off with consumption in fixed proportions, given we assume that marginal propensity to save is constant. At the third nest, CES functions represent consumer decisions between energy and non-energy goods and services.

Government aims to maximize public consumption subject to a budget constraint. Government consumption comprises several goods and services (e.g. social security, healthcare and education). Public expenditure is financed through tax revenues, property and capital rents and transfers.

2.3. Foreign sector

International trade is modelled under the Armington assumption that domestic and imported goods are imperfect substitutes for domestic consumption (Armington, 1969), meaning that total supply in the national economy (for intermediate and final demand) corresponds to a CES composite good that combines domestically produced and imported goods (the so-called “Armington good”; Fig. 4). Likewise, domestically produced goods can be supplied to the inner market or exported to satisfy demand from the rest of the world, under a constant elasticity of transformation supply function. Transfers and rents from the exterior and the consumption by Portuguese tourists abroad are considered exogenous by the CGE, i.e., their values remain constant and in line with the data from the Portuguese national economic accounts and input-output tables.

2.4. Factor markets and closure rules

Two primary production factors are considered: capital and labor. These are perfectly mobile between sectors at the national scale, but immobile internationally. Labor is supplied by a representative consumer owning a fixed endowment of time, which is devoted to labor supply and leisure consumption. The labor market is taken to be imperfect, where involuntary unemployment exists. This is introduced by a wage curve, which negatively relates the real wage level and unemployment rate by an elasticity parameter (the elasticity of real wage to unemployment; approximately -0.1) following Blanchflower and Oswald (1995). Equilibrium is determined by the intersection of the labor demand curve and the wage curve, setting a real wage that is above the market clearing level. Involuntary unemployment results from the difference between labor supply (given by the wage curve) and labor demand, which becomes endogenous to the model. The demand for labor by each production sector is determined by the solution of the producers’ cost minimization problem. Accordingly, the optimal wage becomes endogenous to the model such that it satisfies the market clearance condition.

Capital supply is inelastic and capital demand is determined by the abovementioned cost minimization problem. Capital rents are endogenous to the model, determined by the market clearance condition. Investments correspond to the sum of sectors’ gross capital formation, and is formulated as a Leontief function. National savings correspond to the sum of private and public savings and is, therefore, endogenous to the model. The national net lending/borrowing capacity with respect to the rest of the world is kept constant in the model, and therefore the trade balance (i.e. the sum of exports, imports and the consumption by foreign tourism in Portugal) together with the whole set of exogenous and endogenous variables (as described along the previous sections) represent the closure rules that determine the macroeconomic equilibrium.

2.5. Energy consumption and CO_2 emissions

The model also computes energy consumption in physical units (thousand tonnes of oil equivalent; ktoe). These enter the model based on the sectoral-specific energy consumption per energy carrier (coal, refined petroleum products, natural gas and electricity) in the benchmark. It must be noted that: i) only primary consumption of coal by coal-fired power plants is included in the model because the consumption of coal by other sectors is negligible (DGEG, 2017); ii) renewables are part of primary energy consumption of the “electricity” production sector (following DGEG, 2017). CO_2 emissions resulting from fossil fuel combustion enter the model in fixed proportions to fossil fuels, according to the specific emission coefficient of each fossil fuel per sector, as set in the National GHG Emissions Inventory (UN, 2016).

2.6. Benchmark data and calibration

The CGE model was calibrated to a base year which reflects the initial/benchmark equilibrium. Base year quantities and prices, together with the exogenous elasticities, determine the free parameters of the model’s functional forms (Böhringer and Rutherford, 2013). The core dataset of the model is a Social Accounting Matrix (SAM) for the year 2008, comprising 31 economic sectors (Appendix B). The SAM was built

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[4] Mathematically, the mixed complementarity formulation explicitly incorporates the feature of complementary slackness, that is, complementarity between economic decision variables and associated economic equilibrium conditions.

[5] A full description of the production and consumption functions is provided in Appendix A.

[6] Coal, oil, natural gas, hydropower, onshore wind power, solar photovoltaic, geothermal and biomass.

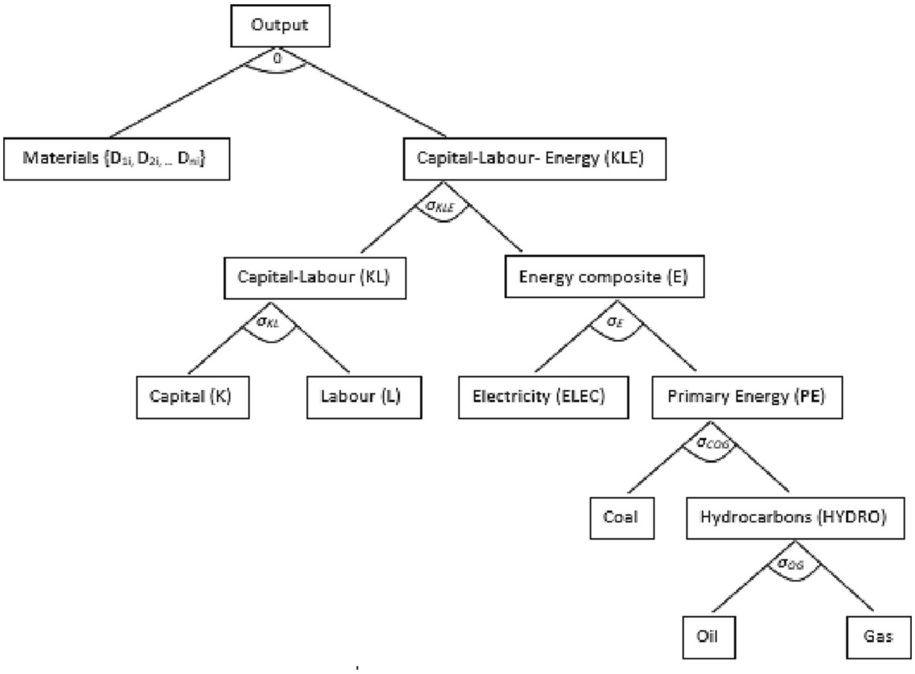

Fig. 1. Production structure.

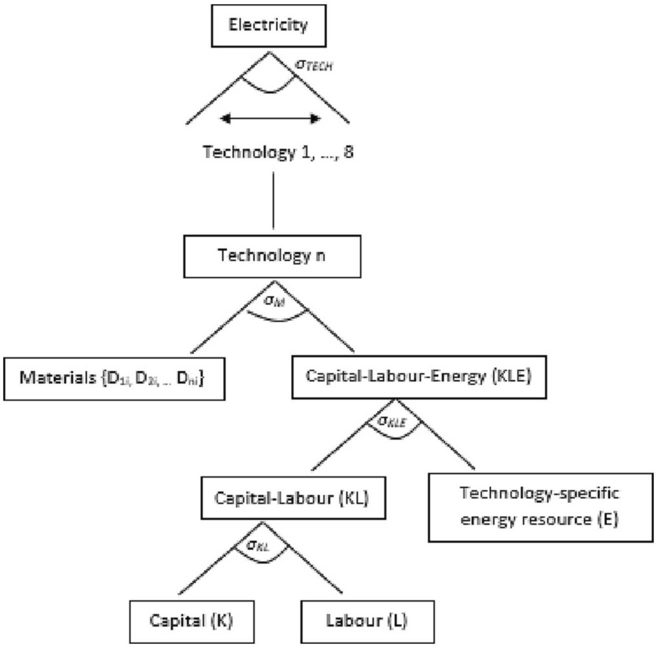

Fig. 2. Electricity sector production structure.
Note: The "technology-specific energy resource" only applies to fossil-fueled technologies; for renewables, the energy sources are provided by nature at zero cost.

by the authors based on Portuguese national accounts and the 2008 symmetric 86-sector Input-Output (I—O) tables for Portugal[7] (DPP, 2011). This initial step was needed because the Portuguese national statitical office does not provide any official SAM. Unemployment data was taken from official statistics (INE, 2016), and elasticities of substitution were taken from the literature (Labandeira et al., 2009, Kemfert and Welsch, 2000; Böhringer et al., 1998; Hertel, 1997; Wing, 2006; EC, 2013; Appendix C).

While I-O tables (and the SAM) provide the macroeconomic comprehensiveness of the model, they lack an adequate representation of the electrical generation sector for the purposes of this research. In order to design a hybrid simulation model, the authors performed a technological disaggregation of the electrical generation sector by using a bottom-up approach. To this end, the SAM's aggregate "Electricity" production sector was split into eight technologies (DGEG, 2016) – three fossil-fueled (coal, oil and natural gas) and five renewable sourced (hydropower, onshore wind power, solar photovoltaic, geothermal and biomass). In particular, the Electricity sector's total output was broken-down according to the cost structure and the output shares of each generation technology from the TIMES_PT database (see Teotónio et al., 2017), a peer reviewed partial equilibrium bottom-up energy system model (Fortes et al., 2019). The unitary costs of electricity generation per technology from the TIMES_PT database were disaggregated into capital costs, fuel costs, and operation and maintenance costs (the latter considered a proxy for labor costs, following Wing, 2008). Although 2008 represents the benchmark year, technological costs for 2015 (from TIMES_PT) were used instead (Table 1). These most recent technological data provide a more accurate portrait of the current Portuguese power sector and are still coherent with the macroeconomic data (given the lower pace at which the national economic structure evolves, as national

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[7] More recent symmetric Input-Output tables for Portugal were made available (INE, 2022). However, national statistics do not show significant structural changes apart from the small change in scale (i.e. the absolute value of GDP). The relative sectoral breakdowns of gross value added (GVA) are broadly similar (see (INE, 2022), and this is what is really relevant for CGE models. Moreover, this is in line with the methodology of the Portuguese Government (APA, 2015), which considers the 2008 sectoral GVA breakdown will persist over the next two decades.

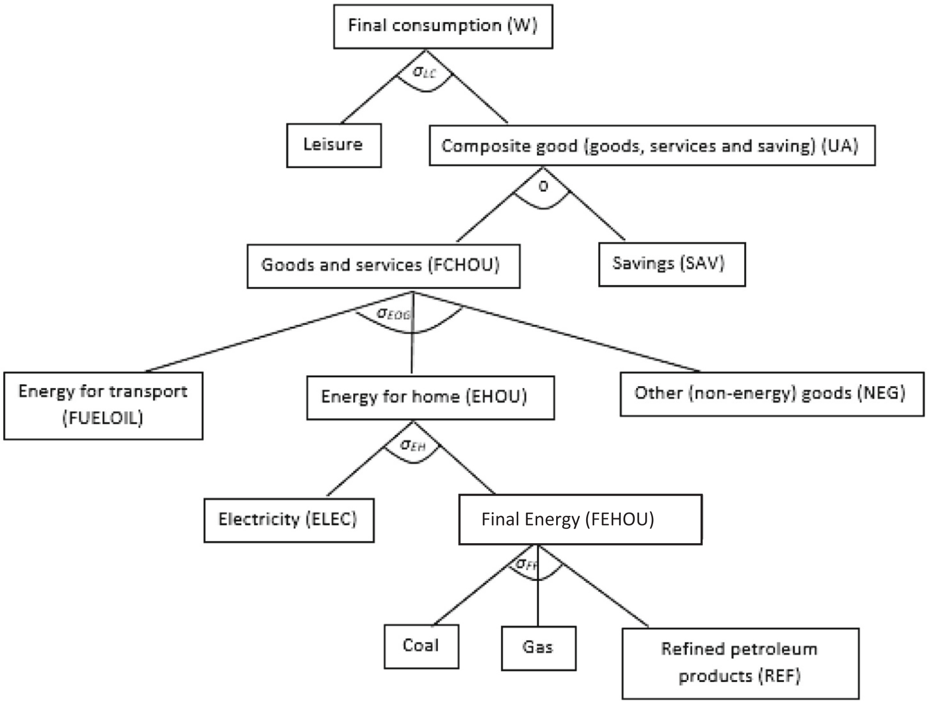

Fig. 3. Consumption structure.

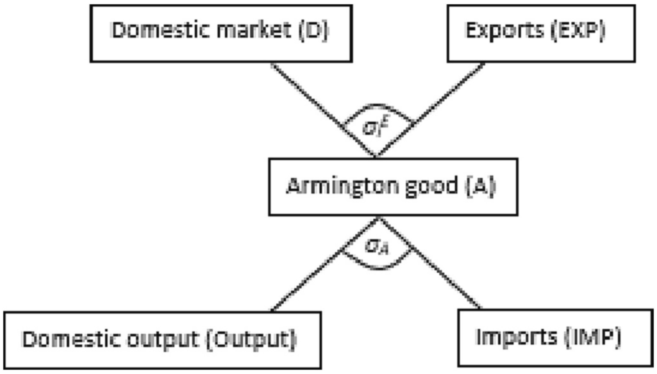

Fig. 4. Nesting production structure of Armington good.

accounts statistics confirm; see (DPP, 2011; INE, 2022). Accordingly, the Portuguese electrical mix considered in the benchmark corresponds to the average of the period 2008–2015. This average provides a better reference point than a single year, which is significantly dependent on the corresponding weather conditions – particularly for hydropower (e.g., hydropower generation in 2015 was 40% lower than in 2014 and 15% lower than the average of the period 2008–2015).

As macroeconomic and technological data derive from different sources (Portuguese I—O tables and TIMES_PT database, respectively), it was necessary to reconcile them so that they could be combined into an integrated framework of analysis. To do so, information on unit generation costs (€/MWh), input cost shares and electricity generated per technology over the period 2008–2015 (see Table 1) were combined to compute the corresponding capital, labor and fuel costs per technology – thereby converting electrical generation from physical units (GWh) into monetary units that are compatible with the SAM. We thus obtained the necessary technological breakdown of the electricity generation sector in the SAM that is consistent with the TIMES_PT database (see Teotónio

Table 1
Electrical generation, unit output costs and cost shares and per technology in the benchmark.

	GWh	%	Unit generation cost (€$_{2011}$/MWh)	Input cost shares		
				Fuel	Capital	Labor
Year	*Average 2008–2015*		*2015*			
Fossil-fueled technologies	**25,908**	**51.02%**				
Coal	11,576	22.80%	35.43 €	42.20%	23.85%	33.95%
Oil	2469	4.86%	56.34 €	83.96%	6.29%	9.75%
Natural gas	11,863	23.36%	44.30 €	81.50%	9.07%	9.43%
Renewable technologies	**24,873**	**48.98%**				
Hydropower	11,588	22.82%	14.44 €	0.00%	68.50%	31.50%
Onshore wind power	9709	19.12%	48.49 €	0.00%	74.59%	25.41%
Biomass	3010	5.93%	185.19 €	68.41%	16.26%	15.34%
Solar photovoltaic	374	0.74%	137.95 €	0.00%	79.62%	20.38%
Geothermal	192	0.38%	62.29 €	0.00%	57.19%	42.81%
Total electrical generation	**50,780**	**100.00%**				

Source: Electrical generation data were taken from (DGEG, 2016). Generation and input cost shares were based on the TIMES_PT database (see Teotónio et al., 2017).

et al., 2017). These data were introduced in the CGE model to provide the bottom-up representation of the electrical generation sector in the benchmark year. Finally, CO_2 emissions in the benchmark were calculated according to the consumption of fossil fuels in our database thereby using CO_2 emission factors per fossil fuel (CO_2 per toe) and economic sector taken from the GHG inventory (UN, 2016) and I—O tables (DPP, 2011). Energy consumption (measured in physical units) was taken from the Energy Balance for Portugal (DGEG, 2017). \.

3. Simulated scenarios

The goal of this paper is to assess the economic impacts of complying with energy efficiency targets that may be defined in different ways. Hence, in accordance with the targets set at the EU level, the goal is to show the impacts of policies directed at savings in primary or final energy consumption. To that end, this paper will simulate a 25% reduction in primary and final energy consumption,[8] using Portugal as a case study. Additionally, the paper simulates a less ambitious objective of 14% in order to assess any convexity feature on the outcomes and conclusions.

All scenarios will generate direct extra costs (and opportunity costs) for economic activities that will drive substitution effects among inputs and changes in consumption behavior. Instead of imposing external cost estimates for energy savings targets into the CGE, the paper simulates the lower and more efficient cost for energy savings by means of a tax tool for simulation purposes only. Accordingly, the hybrid CGE model will simulate the energy-saving targets scenarios through a tax on primary/final consumption of fossil, fossil-fueled and all energy products, whose revenues are recycled via a reduction in indirect taxes on the final consumption of non-energy goods and services such that the fiscal revenue associated with the tax does not affect the public budget.[9]

The rationale for this methodology is twofold. On the one hand, the tax will capture the extra costs (direct or opportunity costs) associated with any specific measure on energy consumption to attain the energy savings targets. On the other hand, the tax provides desirable outcomes, such as "static efficiency", thereby identifying the cheapest compliance option (OECD, 2016). Thus, the paper does not simulate cost functions associated with energy-saving measures on different sectors, according to engineering cost estimates or provided by stakeholders.

The following scenarios were simulated. Scenario PE imposes a tax on primary and secondary energy consumption of fossil fuels by the energy sectors (to be transformed in final energy supply; consumed ktoe of coal, natural gas and oil products); Scenario FE_All imposes a tax on all final energy consumption (consumed ktoe of natural gas, refined petroleum products and electricity [from fossil and renewable sources]); and Scenario FE_Fossil imposes a tax on fossil-fueled final energy consumption (consumed ktoe of natural gas and refined petroleum products) and fossil-fueled electricity production. Concerning this latter, as the homogeneity of the "electricity" commodity makes it infeasible to distinguish renewable and fossil-fueled electricity generation from the consumers' perspective, taxation applies to production instead of consumption. Producers, in turn, transfer the tax burden to consumers (via prices) that end-up as the real taxpayers and, thus, this is equivalent to a tax on fossil-fueled final energy consumption. In this regard, Lin and Jia (2020) discuss the differences between demand and supply-oriented taxes, considering a carbon and a resource tax, respectively. Demand-side taxes (e.g. carbon taxes), whose tax base are energy users, levy on energy consumption, directly reducing energy demand; reduction of energy supply is caused by a decreased energy demand. Supply-side taxes (e.g. resource taxes, such as energy taxes), levy on energy production, thereby increasing energy prices, reducing energy production and affecting energy demand via the price transmission mechanism. Simulated scenarios thus address reductions in primary and final energy consumption of fossil, fossil-fueled and all energy products, and therefore are aligned with the RES and GHG emissions components of policies underlying our analysis (see Table 2).

Finally, note that a tax on primary/final energy will reduce CO_2 emissions when this energy is derived from fossil fuels, given the technical relationship between the combustion of fossil fuels and CO_2 emissions. In that sense, the fossil-fuel tax scenarios can be considered equivalent, from a policy point of view, to a CO_2 tax.

4. Results and discussion

This section presents and discusses the main results of the simulated policies from a sectoral, macroeconomic and environmental perspective.

4.1. Impacts on the energy sector

Achieving energy savings targets leads to demand price hikes in energy products – in particular if the policy target is attained via a tax on final energy consumption (scenarios FE_All and FE_Fos; Fig. 5). That is, energy savings targets on final energy are the most distorting on energy prices. The largest price increase occurs for natural gas, due to the higher ktoe content per Euro (price) of natural gas than other fossil fuels (1.48 ktoe/M€ versus, e.g., 0.66 ktoe/M€ for refined oil products; see DPP, 2011 and DGEG, 2017). Differences are also explained by the lower international prices per ktoe and lower domestic fiscal burden on natural gas as compared to the other fossil fuels. Note that results for coal (prices and output levels) are not reported because there is no production of coal in Portugal and all consumption relies on imports (almost entirely for electricity generation).

Constraining energy consumption induces a generalized decrease in

Table 2
Simulated energy saving target scenarios.

Scenario		Policy target (% energy saving)	Policy variable
Scenario PE	PE_14	−14% primary energy consumption	Primary energy (PE) consumption of fossil fuels (coal, natural gas and refined petroleum products)*
	PE_25	−25% primary energy consumption	
Scenario FE_Fossil	FE_Fos_14	−14% final energy consumption	Final energy (FE) consumption of fossil-fueled energy products (natural gas, refined petroleum products and fossil-fueled electricity)
	FE_Fos_25	−25% final energy consumption	
Scenario FE_All	FE_All_14	−14% final energy consumption	Final energy (FE) consumption of all energy products (natural gas, refined petroleum products and electricity [from fossil and renewable sources])
	FE_All_25	−25% final energy consumption	

Note: *Imports of electricity are not taxed because: i) fossil and renewable sourced electricity imports are indistinguishable; and ii) electricity net imports represent a negligible part of primary energy consumption in Portugal (see DGEG, 2016).

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[8] Recall that the energy efficiency targets for the EU (EC, 2018) and Portugal 2030 (RCM 53/2020) are expressed both in terms of primary and final energy savings.

[9] The recycling mechanism adopted intends to minimize price distortions by the tax change, whose only objective is to restrain energy consumption and reach the energy saving targets. An alternative tax recycling mechanism, notably reducing social security contributions due from the employer, was explored. Impacts of taxation on GDP are worse, that is, recycling the tax via the SSC leads to greater contractions in real GDP, whereas impacts on CO_2 are broadly better, that is, the new mechanism leads to higher reductions in CO_2 emissions. Nevertheless, considering that our primordial objective is to comply with energy saving targets, rather than climate change mitigation, the revenue recycling mechanism adopted in the paper points towards more favorable results in the sense it imposes lower economic impacts and still contributes to reduce emissions. Analyzing different alternative recycling mechanism is out of the scope of this paper.

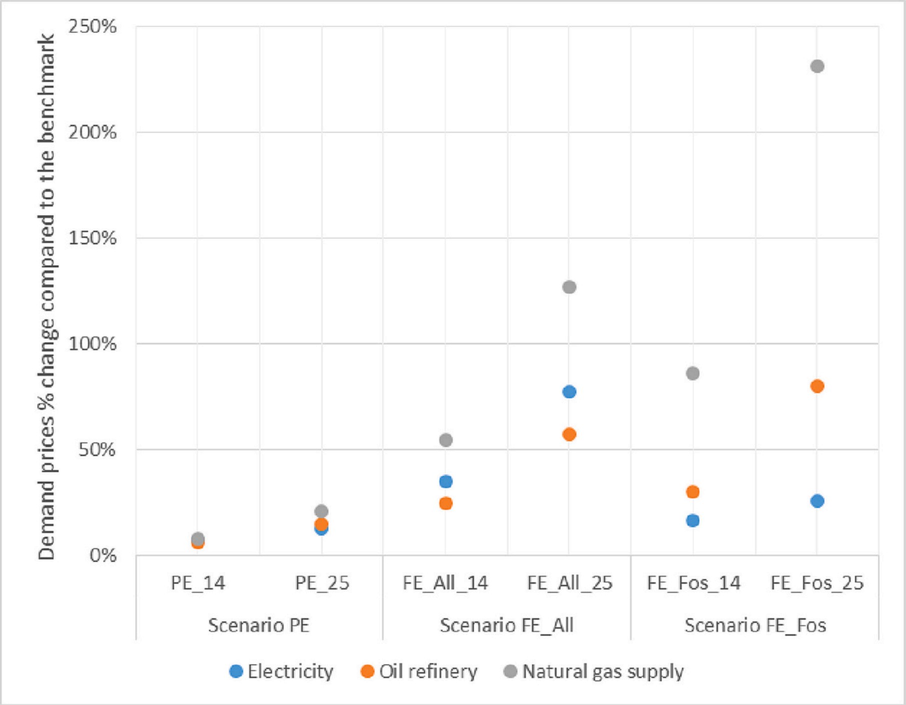

Fig. 5. Impacts on energy demand prices per scenario (% change as compared to the benchmark).

output levels of the energy sectors. Natural gas sector records the strongest impacts (Fig. 6), which is related to the abovementioned strong impacts on prices and to the below explained changes in the electricity mix (the electricity sector in Portugal is the main consumer of natural gas). Contraction of the targeted sector's output is an expected outcome of taxation, and therefore our results are aligned with previous research on the impacts of energy taxes (see e.g. Nong, 2018; Peng et al., 2019).Despite the important impacts recorded in activity levels, there are no significant changes in the economy's energy mix.[10] The share of refined petroleum products (48% in the benchmark) ranges between 45% in the FE_Fos_25 scenario and 49% in the FE_All scenarios (_14 and _25). The share of electricity (28% in the benchmark) increases by up to 34% in the FE_Fos_25 scenario, while it remains constant in the PE and FE_All scenarios. Finally, the share of natural gas (7% in the benchmark) decreases to 4% in the FE_Fos_25 scenario, whilst in the others is remains almost unchanged. Still, the strongest impacts takes place when energy savings are focused on fossil fuels - resulting in lower shares of fossil fuels and, thus, fostering renewable-sourced electricity (see below).

Focusing on the electrical mix, whose changes are mostly explained by each technology's cost-effectiveness and maximum capacity, results show, as expected, that achieving the policy target via energy savings in the consumption of fossil fuels only (scenarios PE and FE_Fos) provides advantages for renewable-sourced electricity generation (Fig. 7). This result derives from the fact that electricity is a homogeneous good and, thus, generation technologies are treated as quasi-perfect substitutes.[11] Hence, as fossil-fueled generation becomes more expensive due to the tax on energy inputs, renewable technologies increase their activity levels to offset the decrease in fossil generation. Our results thus corroborate Freire-González and Puig-Ventosa (2019), who found that, for 'heavy [energy] transition scenarios', as compared to 'non-transition scenarios' (equivalent to our FE_Fos and FE_All scenarios, respectively), domestic production of renewable-sourced electricity increases considerably due to the substitution of fossil-fuels imports.Under a 14% reduction in energy consumption, wind and hydropower output increase, respectively, by up to 42% and 22% in the PE scenario, and by up to 54% and 61% in the FE_Fos scenario. Under the energy saving target of 25%, wind and hydropower output increase, respectively, by up to 54% and 44% in the PE scenario, and by 54% and 71% in the FE_Fos scenario. In the PE_25 and FE_Fos_25 scenarios it represents the maximum technical potential of wind power and, for the FE_Fos_25 scenario, the maximum technical potential for hydropower under average hydrologic conditions (see APA, 2012), as our simulations relate to 2030 horizon and therefore there is no time for significant extra capacity building. If the energy saving target covers final consumption of all energy products (scenario FE_All), renewables do not have a comparative advantage over fossils. As a result, the electrical mix is not so significantly different from the benchmark, and, hence, there are no ancillary benefits (e.g. pursuing other energy-climate goals such as the targets for the share of renewables in final energy consumption).

Regarding the previous results, it is clear that PE_25 scenario is preferable to FE_Fos_14 scenario (and also FE_All scenarios) regarding the impacts on the energy sector: similar reduction on electricity production, similar results on renewables penetration, but much lower impact on prices.

4.2. *Impacts on the non-energy sectors*

As to the non-energy sector activity levels, smaller variations occur if the energy saving target is achieved through reductions in primary energy consumption[12] (Fig. 8). Results show a generalized decrease in activity level in almost all cases. Service sectors (namely public,

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[10] Consumption of heat, waste and renewables without electricity by end-use sectors (households, industrial and services sectors) was not included in the CGE model. Therefore, their share in the benchmark (17% of final energy consumption) is assumed to be kept constant in all scenarios.

[11] We assume that the elasticity of substitution between technologies is 10, following Wing, 2006, as to prevent corner solutions (i.e. all electricity is generated by the cheapest technology).

[12] Results for policies aiming at a 25% reduction in energy consumption lead, in almost all sectors and scenarios, to impacts that are twofold the ones obtained for a 14% reduction. The former results are presented in Appendix E.

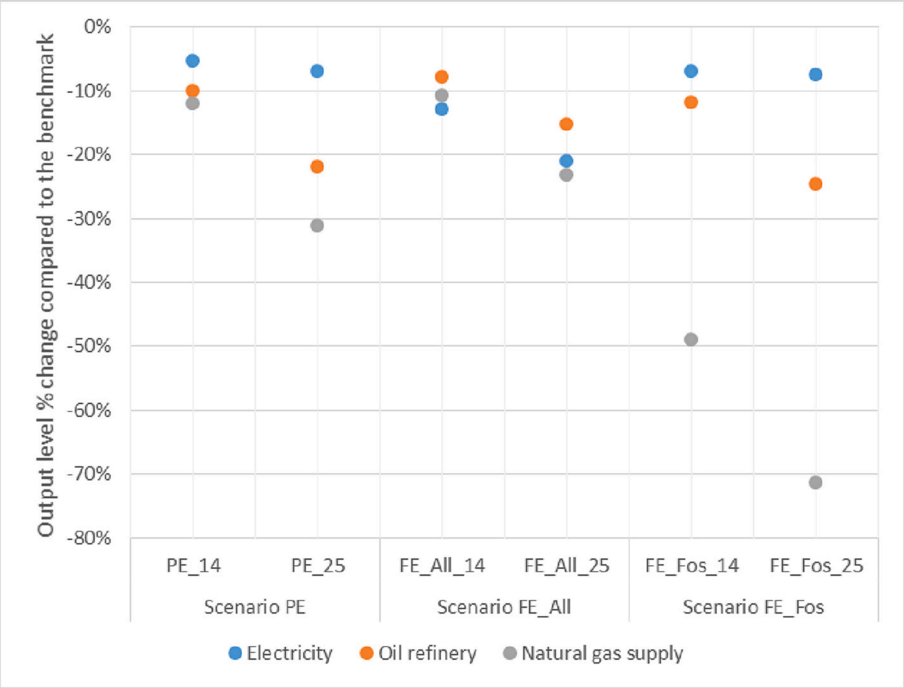

Fig. 6. Impacts on output levels of energy sectors per scenario (% change compared to the benchmark).

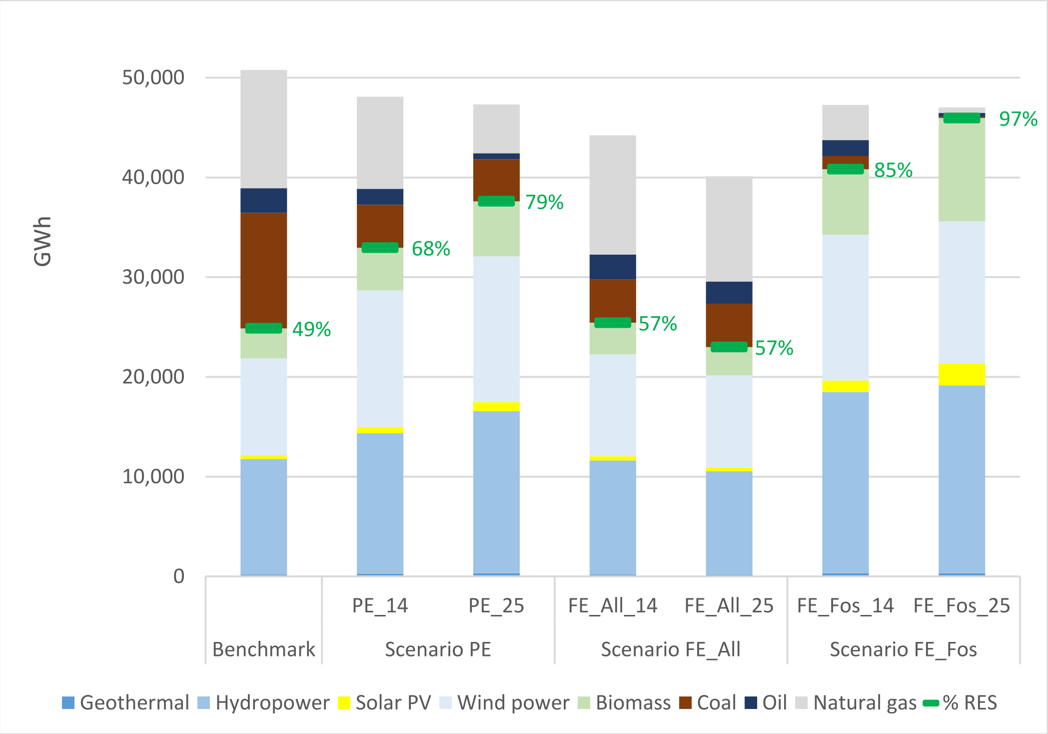

Fig. 7. Electricity generation mix per scenario (GWh and share of RES).

financial and other personal services) maintain their activity levels, as their production costs are barely affected given their low energy consumption. Sectors with relevant levels of energy consumption (such as accommodation and food service activities, and manufacturing of food and textiles) also maintain their activity levels as the effect of the energy tax is mitigated via fiscal revenue recycling (reduction of indirect taxes on goods and services). Within the mechanism adopted, it turns out that the effect of energy taxation on production costs is counterbalanced by a reduction in the tax burden in the final consumption of goods and services supplied by these sectors. Hence, taxation results in moderate changes in consumer prices and reasonable inflation rates for all scenarios (see also Section 4.3). By contrast, energy intensive sectors record noticeable reductions in their production levels (e.g. between −2.0% and − 6.7% for non-metallic mineral products). This negative effect derives, first, from the preponderance of energy inputs in the production function (increasing production costs) and, second, from the fact that

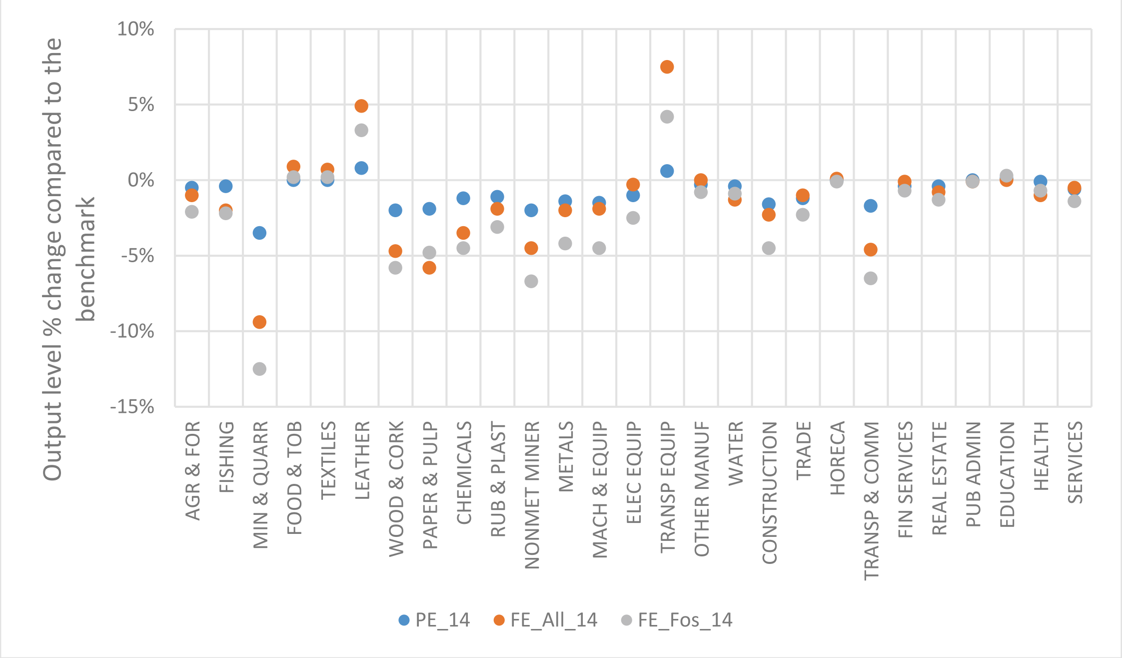

Fig. 8. Sectoral impacts on output levels of non-energy sectors per scenario (% change compared to the benchmark).

this effect could not be completely offset via fiscal revenue recycling (thus resulting in increasing prices and reducing activity levels). Overall, the most affected sectors represent around 17% of GDP in the benchmark and in the simulated scenarios and, therefore, none of the simulated policies induces significant structural changes in the national economy. Peng et al. (2019), who applied an energy excise tax aimed at restraining energy consumption, also found sound differences on the impacts over the sectoral output between the energy and non-energy sectors; despite the model is more aggregated than ours (11 sectors against 31), simulated impacts go in the same direction, with the manufacturing and transport sectors recording the strongest impacts.

4.3. *Macroeconomic impacts*

Results show that the macroeconomic impacts of achieving energy saving targets are broadly negative, irrespective of the tax base (Table 3). The energy tax increases energy prices and production costs and, thus, reduces profits. Accordingly, producers rearrange production processes – in particular the use of energy and other inputs (notably capital and labor) as to minimize the impacts on production costs. Simultaneously, sectoral activity levels contract and, as a consequence, demand for inputs and labor decrease, and involuntary unemployment increases. Still, the impacts of taxing primary energy consumption (scenario PE) are the less severe.

The fiscal revenue recycling mechanism implies that consumer prices do not increase considerably following the increase in production costs and, thus, the aggregate effects on final consumption of non-energy products are negligible. While inflation is moderate, its combined effect with lower nominal wages results in a slight decrease in real wages. Moreover, this decrease in real wages is associated with an increase in the rate of involuntary unemployment.[13] Overall, a decrease in real GDP is observed in all scenarios. Such contraction, is, indeed, a common result in literature on the impacts of energy taxes (see e.g., Hu et al., 2021; Nong, 2018; Freire-González and Puig-Ventosa, 2019).From a macroeconomic perspective, attaining the energy saving targets by taxing primary energy consumption (scenario PE) is most appropriate as it results in smaller reductions in GDP and lower inflation rates, while the effects on unemployment and real wages are limited. A comparison of the FE_ scenarios shows that the most cost-effective solution (i.e. value-added generation versus energy savings) is to make no distinction between fossil and renewable sources (scenario FE_All). This is related to the fact that taxing all energy consumption implies that the tax burden is spread across a larger tax basis (which reduces the tax rate to achieve a certain energy saving) and, thus, the resulting economic disruptions are smaller.

4.4. *Impacts on energy security*

The reduction in energy consumption leads to an improvement in the energy trade balance for all scenarios (i.e. lower deficit, as Portugal is a net energy importer; Table 4). The smallest deficit reduction occurs for the PE scenario, where national energy needs are increasingly satisfied by imports of final energy products and electricity. The largest deficit reduction occurs in the FE_Fos scenario, despite the electricity trade balance deteriorates in response to the lower activity level of the fossil-fueled energy sectors, and domestic power generation decreases (between −6.9% and – 7.6%; Figs. 6 and 7). The impacts obtained for PE scenario compare with the findings of Lin and Jia (2020) in that an energy tax will increase fossil energy imports to circumvent the rise in prices of domestic energy.The energy-saving target scenarios assessed

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[13] Welfare, measured by Hicksian Equivalent variation in real income, barely changes after the energy tax. This occurs because, as impacts on unemployment are minor, real wages remain stable and, consequently, the opportunity cost of leisure (on which agents' welfare depends) also remains unchanged. Thus, as devoted time to leisure is kept constant, and changes on final consumption of non-energy products are negligible, agents' welfare is not impacted by the simulated policies.

Table 3
Macroeconomic impacts per scenario (% change compared to the benchmark).

Macroeconomic variable	Scenario PE		Scenario FE_All		Scenario FE_Fos	
	PE_14	PE_25	FE_All_14	FE_All_25	FE_Fos_14	FE_Fos_25
Real GDP at market prices	−0.5	−1.1	−2.3	−5.1	−2.6	−6.2
Consumer Price Index	0.3	0.5	0.5	1.3	1.1	2.5
Real wage	−0.2	−0.2	0.0	0.0	−0.2	−0.3
Unemployment rate	1.3	2.6	0.0	0.0	1.3	3.9

Table 4
Impacts on energy trade balance (% change compared to the benchmark) and on energy dependence, per scenario.

	Benchmark (M€)	Scenario PE		Scenario FE_All		Scenario FE_Fos	
		PE_14	PE_25	FE_All_14	FE_All_25	FE_Fos_14	FE_Fos_25
Mining of coal; extraction of crude petroleum and natural gas	−7478.22	−13.4%	−26.5%	−10.8%	−18.7%	−21.1%	−35.1%
Refined petroleum products	−679.93	88.1%	203.6%	−7.6%	−14.9%	−8.1%	−19.7%
Electricity	−636.77	18.2%	35.6%	−6.2%	−17.5%	49.8%	89.6%
Natural gas (distributed)	−0.12	93.4%	183.5%	−10.7%	−23.1%	−47.1%	−69.4%
Total energy trade balance	**−8795.04**	**−3.3%**	**−4.2%**	**−10.2%**	**−18.3%**	**−14.9%**	**−24.9%**
Energy dependence (%)	**76.3%**	**70.9%**	**65.7%**	**74.7%**	**74.8%**	**64.9%**	**57.8%**

improve, also, energy security, measured by the dependence on net imports (Table 4), due to the simultaneous reduction in energy consumption and increase in endogenous renewable-sourced energy. Scenario FE_All presents the smallest progress because the incentive to shift from imported to renewable domestic energy sources is limited given that all energy products are taxed. In line with results on trade deficit, the FE_Fos scenario provides the best outcomes regarding energy dependence, but it is worth to stress there are no substantial differences with respect to PE_25 scenario.

4.5. Impacts on energy intensity

Final energy intensity falls in all scenarios (Fig. 9). As expected, largest decreases are observed for the most energy intensive sectors (in particular manufacturing and transport). Scenarios FE_All and FE_Fos lead to similar changes in total energy intensity, despite sectoral differences, which are explained by the incidence base of energy saving targets (all energy products and fossil fuels, respectively) and the sectoral energy mix. Note that energy intensity in households increases in the FE_Fos scenarios. This occurs because, following the taxation of fossil fuels, the electricity price decreases in relative terms and, therefore, there is a shift to electricity consumption. In other words, the resulting decrease in consumption of refined petroleum products and gas is offset by electricity and, overall, energy consumption by households slightly increases – thus increasing energy intensity.

The decomposition of aggregate energy intensity changes into the contribution of changes in energy consumption and GDP (as energy intensity results from the ratio energy consumption/GDP) shows that improvements are mostly due to a reduction in energy consumption (see Fig. 10). Thus, energy intensity improvements derive, mainly, from lower energy needs per output and, less so, from structural changes in the economy at the aggregate level (i.e. from a shift to tertiary sector activities with lower energy consumption), as the sectoral GVA structure is kept relatively unchanged between scenarios.

Caution should be exercised with respect to the interpretation of changes in energy intensity, as these should not be understood straightforward as improvements in energy efficiency. In other words, the 22.6% energy intensity reduction in the FE_Fos_25 scenario does not necessarily represent a better improvement on energy efficiency than the 8.3% reduction attained in the PE_25 scenario, because in both cases the political target is similar: a 25% reduction in energy consumption (of, respectively, final and primary energy). Besides, the (%) contribution of savings in energy consumption to reduce energy intensity is larger for the PE_25 scenario (as shown in Fig. 10).

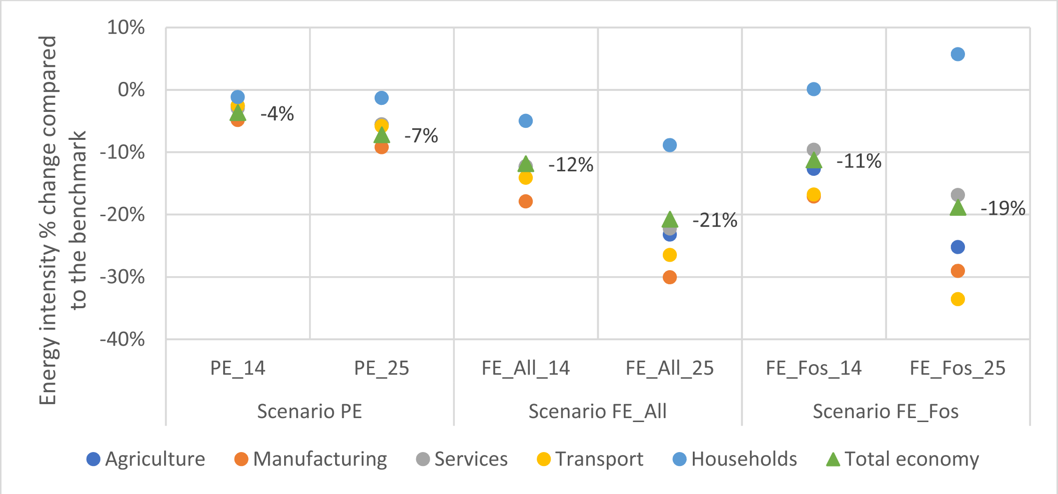

Fig. 9. Impacts on intensity of final energy consumption per scenario (% change compared to the benchmark).

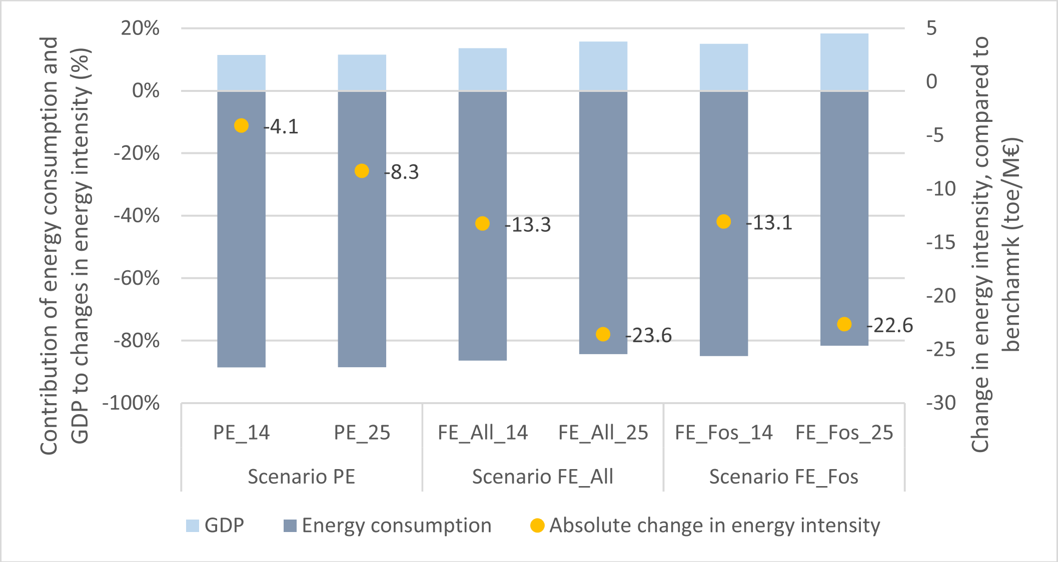

Fig. 10. Decomposition of energy intensity changes into components per scenario.

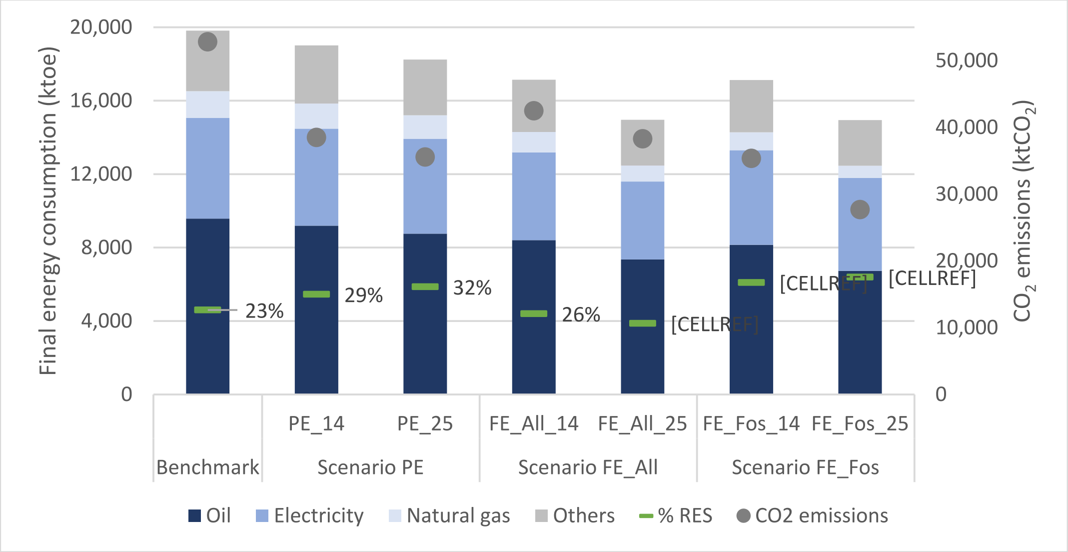

Fig. 11. Final energy consumption (ktoe), CO2 emissions (kt) and share of RES per scenario (note: share of RES is estimated considering the share of renewable electricity plus heat, waste and renewables without electricity).

4.6. *Progress towards policy goals for renewables and CO_2 emissions*

Results highlight the effectiveness of energy savings targets focused on fossil fuels' consumption to strengthen the role of RES in final energy consumption (Fig. 11). Moreover, lowest levels of fossil fuel consumption and largest shares of RES in the electrical mix produce noticeable reductions in CO_2 emissions. With a 14% reduction in energy consumption, CO_2 emissions decrease between 32% (FE_All scenario) and 43% (FE_Fos scenario); considering a a 25% energy saving, CO_2 emissions decrease between 38% and 55%, respectively (Fig. 11). Once again, the environmental benefits of the FE_All scenario are the smallest because fossil and renewable energy sources are indistinctly treated and, thus, the CO_2 emitting sectors maintain a prevailing role in the national energy mix. Three scenarios broadly ensure national compliance with the 2030 target for GHG emissions (45% to 55% reduction by 2030 as compared to 2005 RCM 53/2020), with CO_2 emissions decreasing by between 43% (PE_25, FE_Fos_14) and 55% (FE_Fos_25) as compared to 2005 levels. In this respect, it should be noted that our results may be rather conservative, as we do not model biomass and other renewable energy consumption except in the power sector (recall that it is assumed that the share of renewable energy by end use sectors, except for the power sector, remains constant in all scenarios). Again, our results are coherent with previous literature: considering a broad range of pollutants, Freire-González and Puig-Ventosa, 2019, found an overall improvement in emissions resulting from electricity taxation, which is directly correlated with the penetration of renewables in the power mix, whilst Hu et al., 2021 found that fossil energy taxes reduce carbon emissions but have variable impacts on other pollutants, thereby concluding for the superiority of carbon taxes (over resource taxes) for climate mitigation.

Regarding the relationship between primary and final energy consumption in each scenario, results point towards significant differences. In particular, 14% and 25% reductions in final energy consumption lead to −12% and − 20% primary energy consumption in the FE_All scenarios, respectively, but −21% and − 32% in FE_Fos scenarios.The largest difference recorded in the FE_Fos scenario is explained by the dominant role of renewable-sourced electricity, and the assumption that all renewable primary energy consumption for power generation is transformed into electricity without any losses. Therefore, a policy aiming at a reduction in fossil fuels (FE_Fos) will reduce the sources of final energy bearing some losses in their transformation from primary to final energy, hence tightening the gap between primary and final energy consumption. In other words, it will increase the efficiency of the energy system by providing larger reductions in primary energy than final energy consumption. In the same vein, the simulated 14% and 25% reductions in primary energy consumption (PE_14 and PE_25 scenarios) will reduce final energy consumption by, respectively, ~4% and ~ 8%, thus delivering the best improvement in the efficiency of the energy system among all scenarios.

4.7. Sensitivity analysis

The robustness of the model results is assessed through a sensitivity analysis, simulating the described scenarios with alternative elasticities of substitution available in literature (i.e., we ran the model using the elasticities presented in Appendix D to compare results with those obtained using the elasticities presented in Appendix C). The impacts on key variables are broadly similar, though smaller, as compared to those obtained for the reference elasticities (Fig. 12). Both elasticities in Appendix C and D have been used in the literature. For our sensitivity analysis, the focus is on differences for elasticities of substitution between energy inputs which are the key parameters driving the CGE results. Appendix D shows elasticities between electricity and hydrocarbons 50% lower than elasticities used in this paper (Appendix C), and the same applies for elasticities between refined oil products and natural gas, as showed in Appendix D. Elasticity of substitution between coal and hydrocarbons is almost null in Appendix D. Thus, the lower the elasticity of substitution of energy products, the lower the flexibility to adaptation of the economy to the stringent energy savings targets, and the higher the economic and efficiency costs. The sensitivity approach followed in this paper is a well-established practice (and the most common practice) within literature that use applied CGE models to simulate impacts of policies (e.g. Böhringer et al., 2022), even though there are available some alternative systematic sensitivity analysis approaches in the literature like Monte Carlo and Gaussian quadrature methods (e.g. Preckel et al., 2011). Despite the important changes in elasticities of substitution between energy inputs, differences in real GDP are less than 0.2 p.p. (e.g. PE_14 versus PE_14_sens); differences in final energy consumption vary between 0.6 p.p. (PE_14 scenario) and 3.9 p.p. (FE_All_25 scenario); and differences in energy intensity vary between 0.7 p.p. (PE_14 scenario) and 4.2 p.p. (FE_All_25 scenario). As to the energy sectors, output levels of natural gas supply and oil refinery sectors vary up to 4 p.p. in the FE_All and FE_Fos scenarios, whereas energy demand prices remain almost unchanged in the three energy sectors. Thus, overall reported changes are coherent with the reference results – confirming the robustness of our model.

5. Policy implications

The results of this research deliver ample spatial and temporal patterns beyond the Portuguese economy, thus providing general lessons for academics and policymakers. From a temporal perspective, energy savings targets at the EU and national scales are set for the medium term (2030), while some energy efficiency improvements may not be realized immediately given that some technological development take time to become fully available at competitive prices. Hence, energy fiscal policies may be needed to meet energy savings targets (with consequences for GDP in the short term) and to provide dynamic incentives to pursuit continuous energy efficiency improvements. Consequently, the level and timing of energy savings targets should, preferably, be aligned with energy efficiency improvements as to avoid negative economic impacts and to achieve environmental targets (in line with Peng et al., 2019). Our results suggest that achieving the energy efficiency policy targets via energy savings in primary energy consumption of fossil fuels is the most cost-effective (i.e. value-added generation versus energy savings) of the simulated policies. In comparison with policy options focused on final energy savings, it generates the lowest macroeconomic distortions (e.g. changes in final energy prices and decreases in GDP) and simultaneously provides reasonable ancillary benefits (e.g. reduction in energy dependence and CO_2 emissions; increase in the share of renewables in the energy mix; and higher efficiency levels of the energy system). This outcome is explained by two simultaneous effects of the energy tax on primary energy consumption:

(i) targeting primary energy consumption produces strongest incentives to improve the efficiency levels of the energy system.

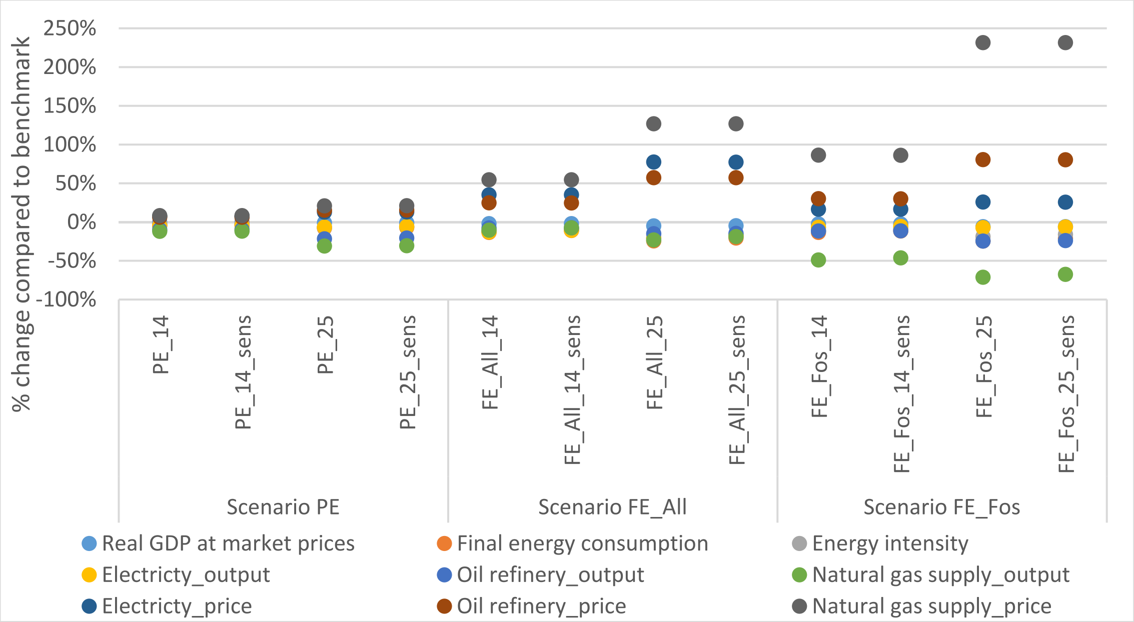

Fig. 12. Sensitivity analysis - Economic impacts of simulated energy saving targets' scenarios (% change compared to the benchmark).

This occurs because the incentives are more intensive for final energy producers (the agents supplying final energy to the markets) which, in many cases, are the economic agents exhibiting lower efficiencies and higher energy losses. Actually, in the process of transforming primary energy into final energy there are considerable energy losses (e.g. in the case of electricity production with natural gas we need 3 kWh of gas to produce 1 kWh of electricity, approximately) even if the thermal power plant is managed efficiently. That is, there are technical issues preventing higher energy efficiency levels, notably the fact that most of the energy that goes into a thermal power plant is vented off as waste heat. Following the previous example, 1MWh reduction in electricity supplied by gas turbines will reduce natural gas combustion by 3 MWh, thus delivering more than proportional reductions on electricity consumption by end consumers. Thus, transformation losses are the major reason why designing energy saving policies targeting primary energy consumption is the most effective option;

(ii) targeting primary energy consumption is more beneficial from an economic perspective because most economic activities are final consumers of energy (and therefore not directly liable for the energy tax). Therefore, energy savings in primary energy consumption of fossil fuels induces the smallest reduction in final energy consumption (the only relevant energy for firms and households).

In particular, a 25% reduction target on primary energy will support the national compliance with the 2030 target for GHG emissions (45% to 55% reduction by 2030 as compared to 2005; RCM 53/2020), with a 43% reduction on CO_2 emissions as compared to 2005 levels. And that will be achieved at half of the impacts on GDP and much lower distortions on energy prices than a 14% reduction target on fossil fuel energy alone, while the effects on unemployment and real wages are limited. Besides, a 25% reduction target on primary energy will deliver better results than any target on all final energies (14% and 25%). These conclusions are of utmost importance for the EU energy policy and provide valuable insights for EU Member States, notably to address the actual energy crisis and the new geopolitical scenarios delivered by the Ukraine war. National energy efficiency targets can be defined based on primary or final energy savings, or even energy intensity (EC, 2018). Our results suggest that targets based on final energy may be more harmful in many aspects and so primary energy targets are preferable. In the same vein, primary energy targets deliver the lowest reduction in energy intensity and so energy intensity targets become misleading, thus reinforcing some previous scientific results (e.g. Rodriguez et al., 2020). These results are of outstanding value because the European Commission is currently in the process of revising the European Energy Taxation Directive (ETD; EC, 2021b) which is supposed to finalize in 2023. In its current version, the proposal: (i) provides a new structure for minimum tax rates based on the real energy content and environmental performance of fuels and electricity; (ii) enlarges the tax base by including more products and sectors (i.e., eliminating some exemptions and reductions); and (iii) includes significant reductions in the ability for Member States to deviate from general ETD guidelines. However, the revision of ETD does not change the general rule based on the principle that taxation should be levied on end products, regardless of inputs used in their production. Our results just provide a justification for the opposite: the advantage of taxes on energy inputs by the energy sectors instead of final energy goods. Because of two main reasons: (i) it delivers greater energy efficiency to the system at lower economic costs, thus better contributing to the EU climate objectives and (ii) it will provide the right price signals to final energy consumers considering that the tax incidence is determined by the relative elasticities of supply and demand (i.e., legal versus economic tax incidence).

Results also show that uniform fiscal policies burdening consumed energy quantities (ktoe) may have unexpected effects on energy markets and undesired consequences from an environmental perspective. Natural gas records the strongest impacts, as compared to refined petroleum products and electricity inputs. This is due to the larger ktoe to Euro ratio of natural gas as compared to other fossil products, which results in a greater relative weight of the energy tax on the price of natural gas. As a result, any policy aiming at energy savings by taxing the energy content of commodities with higher energy intensity (e.g. ktoe content in one € price) will produce stronger impacts on energy markets (price and consumption levels). In particular, it will impose a larger tax burden on natural gas despite it may represent the fossil energy product with lower environmental impact (as natural gas is responsible for less GHG emissions as compared to refined petroleum products, for example). Besides, recent developments in gas markets since 2021 suggest that natural gas disturbances deliver disproportionate distortions in electricity markets (considering their small share of the energy mix in many markets). That is possible because of marginal rules for setting electricity prices, and that is independent of the fact whether gas is the marginal technology for a particular hour of the pool (e.g. hydropower sets prices according to its opportunity costs, which many times are related to the price of gas thermal plants). This outcome highlights that the relationship between improvements in energy savings and reductions in GHG emissions is not straightforward. It suggests that it is more suitable to set different tax rates for distinct energy commodities according to their ktoe to price ratio, carbon content and regional economic structure, in line with conclusions from e.g. Nong, 2018 and Peng et al., 2019 that show that energy efficiency measures should be coupled with mitigation policies in order to avoid undesirable results.

Finally, and following the comments raised in the previous paragraph, our results show that taxing final consumption of all energy products leads to the larger impacts on electricity prices and outputs. Considering that this policy spreads the fiscal burden across a larger tax basis (i.e. implies lower ktoe tax rates) than taxing final consumption of fossil fuels only, this represents a counterintuitive result in public economics because lower impacts are usually linked to larger tax basis (i.e. taxation of final consumption of all energy products at lower ktoe tax rates).

6. Conclusions

Public policies fostering sustainability encompass, without exception, concerns with dematerialization and resource efficiency, as these are key factors to decouple economic growth from resources use. This issue becomes particularly relevant with regard to energy. Such relevancy is patent in the international framework of climate policies and in all current and upcoming EU energy and climate policies and corresponding targets. In particular, the EU aims at a 32.5% improvement in energy efficiency by 2030 (and possible further increase up to 36%), as compared to projections of the expected energy use in that year. These objectives are becoming even more relevant to address the energy crisis and the new geopolitical scenarios delivered by the Ukraine war. Accordingly, the objective of this paper is to assess the sectoral (energy and non-energy sectors), economic (GDP, unemployment and energy security) and environmental (renewables, energy intensity and CO_2 emissions) impacts of tentative energy saving targets (25% and 14% reductions compared to the benchmark), using a hybrid static CGE model for a small open economy that comprises 31 production sectors, a technological disaggregation of the electricity production sector and labor market imperfections.

The three simulated policies consist in achieving energy efficiency targets through reductions in primary or final energy consumption of fossil fuels or all energy products. To that end, the paper does not impose external cost estimates for energy savings targets into the CGE (e.g. cost functions associated with energy-saving measures on different sectors, according to engineering cost estimates or provided by stakeholders). Instead, the paper simulates the most cost-effective (i.e. value-added generation versus energy savings) policy to attain energy savings by means of a tax tool for simulation purposes, following the static and dynamic efficiency rationale attached to environmental taxes.

Achieving energy savings targets through energy taxation may result in reductions in sectoral activity levels, notably in the most energy-intensive ones (e.g. manufacturing) thereby possibly leading to GDP contractions. At the same time, gains in energy savings improve the energy trade balance and energy dependence rate, indicators of utmost importance for energy security. The role of renewable electricity in the energy mix is strengthened, contributing to energy transition, with increasing shares of RES and decreasing levels of GHG emissions, although this poses additional challenges due to the variability and uncertainty of renewable electricity. Finally, energy intensity is reduced mainly due to lower energy consumption, thus advancing in the decoupling of economic growth and energy use.

Thus, results show that meeting energy efficiency targets (defined as energy savings) through energy taxation result in negative economic impacts – in line with the conclusions obtained by e.g. Nong, 2018, Freire-González and Puig-Ventosa, 2019 and Peng et al., 2019. These outcomes seem contrary to the ones obtained by Bataille and Melton, 2017, Figus et al., 2017 and Mahmood and Marpaung, 2014, which show that energy efficiency improvements lead to an increase in GDP, but these divergent conclusions are explained by the difference in adopted measures. In our analysis, energy efficiency targets (expressed in energy savings) are achieved using energy fiscal policies subject to existing energy technologies, while in Bataille and Melton, 2017 and Mahmood and Marpaung, 2014, energy efficiency targets are achieved through exogenous technological energy efficiency improvements. With regard to the latter option, as explained for instance in Bataille and Melton, 2017 (p.124), they do not "include endogenous R&D [investments] or cumulative penetration cost dynamics, the more formal definition of endogenous technology innovation". That is the key to understand the positive impact of energy efficiency on GDP in Bataille and Melton, 2017, Figus et al., 2017 and Mahmood and Marpaung, 2014, because of two reasons: (i) it is cost free and (ii) the improvement on energy intensity may be the outcome of an improvement in labor productivity without any improvement in energy efficiency (e.g. energy savings) as suggested in Rodríguez and Pena-Boquete, 2017.

Our results suggest that achieving the energy efficiency policy targets via energy savings in primary energy consumption of fossil fuels is the most cost-effective (i.e. value-added generation versus energy savings) of the simulated policies. This occurs not only because energy savings in primary energy consumption of fossil fuels induces the smallest reduction in final energy consumption (the only relevant energy for firms and households) but also due to the losses in the transformation from primary to final energy. Our results also suggest that targets based on energy intensity goals may be misleading because primary energy targets deliver the lowest reduction in energy intensity. These are valuable lessons for policymakers as national energy efficiency targets can be defined based on primary or final energy savings, or even energy intensity (EC, 2018). Finally, results show that uniform fiscal policies burdening consumed energy quantities (ktoe) may have unexpected effects on energy markets and undesired consequences from an environmental perspective. For instance, natural gas records the strongest impacts, as compared to refined petroleum products and electricity.

Our analysis presents some caveats. First, we use a static general equilibrium model which only allows for a comparative-static analysis, not capturing the economy's adjustment path towards the envisaged targets. Second, the model does not simulate final renewable energy consumption (except for the consumption of renewable electricity), implying that our results may be conservative in the case of RES share (i.e. larger positive impacts on renewable energy may be possible). Third, the economic impacts of policies are the outcome of exogenous elasticities of substitution estimated from historical data. However, a sensitivity analysis confirmed the robustness of our results. Fourthly, the technologies' costs differ, at present, from their 2015 values, but technologies' costs have been subject to market evolution or external shocks like, in recent years, the COVID-19 pandemic and the Ukraine war. However, considering (i) the exploratory character of this analysis, which relies on distinct impacts of alternative energy taxes aiming at reducing energy consumption, as well as that (ii) macroeconomic data and energy generation costs are coherent for the same time span, this does not bias the results nor the conclusions / lessons that can be learned. Finally, understanding the social acceptability of simulated scenarios, which could involve a deep stakeholder consultation process, is not considered in the present analysis. This topic should be addressed in future research.

Despite these limitations, this paper fills a gap in literature regarding the quantification of the real impacts of binding energy-saving targets set by public policies and provides insights in unexpected outcomes that may be considered in any climate/energy policy-making process in the international context. Furthermore, it constitutes the first quantitative assessment of the economic impacts that energy efficiency targets may pose to the Portuguese economy and presents sectoral detail that allows for the design of fine-tuned public policies. Hence, the approach can be replicated to other countries and regions that are committed to energy efficiency targets, as these necessarily imply a trade-off between economic growth and environmental goals.

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CRediT authorship contribution statement

M. Rodríguez: Conceptualization, Methodology, Software, Formal analysis, Writing – review & editing. **C. Teotónio:** Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing. **P. Roebeling:** Writing – review & editing. **P. Fortes:** Investigation, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors have no conflict of interest to declare.

Appendix A. Model description

A full description of the production and consumption functions is provided below (see Figs. 1 to 4 in the text for a depiction of production and consumption structures). They represent constant elasticity of substitution (CES) functions except for eqs. 1 and 14, which correspond to Leontief functions, and eq. 17, which is a Cobb–Douglas function.

There are 31 production sectors, denoted by i, which are described in detail in Appendix B. Greek letters stand for scale {α, λ, γ, ϕ} and elasticity of substitution {σ} parameters. Latin letters stand for share parameters in the production and consumption functions {a, b, c, d, s}. Subscripts A and H

stand for production activity and households, respectively.
Production

Non-electricity production sectors

Eq. (A.1) - Output from sector i {KLE + intermediate inputs}

$$Output_i = min\left(\frac{KLE_i}{c_{0i}}, \frac{CID_{1i}}{c_{1i}}, \dots, \frac{CID_{ni}}{c_{ni}}\right)$$

Eq. (A.2) - $\mathrm{KLE_i}$ {composite input KL + Energy (E)}

$$KLE_i = \alpha_i\left(a_i KL_i^{\frac{\sigma_i^{KLE}-1}{\sigma_i^{KLE}}} + (1-a_i)E_i^{\frac{\sigma_i^{KLE}-1}{\sigma_i^{KLE}}}\right)^{\frac{\sigma_i^{KLE}}{\sigma_i^{KLE}-1}}$$

Eq. (A.3) - $\mathrm{KL_i}$ {composite input Capital (K) + Labour (L)}

$$KL_i = \alpha_{iKL}\left(a_{iKL}L_i^{\frac{\sigma_i^{KL}-1}{\sigma_i^{KL}}} + (1-a_{iKL})K_i^{\frac{\sigma_i^{KL}-1}{\sigma_i^{KL}}}\right)^{\frac{\sigma_i^{KL}}{\sigma_i^{KL}-1}}$$

Eq. (A.4) - $\mathrm{E_i}$ {composite input Electricity (ELEC) + Primary energy (PE)}

$$E_i = \alpha_{iE}\left(a_{iE}ELEC_{iA}^{\frac{\sigma_i^{E}-1}{\sigma_i^{E}}} + (1-a_{iE})PE_i^{\frac{\sigma_i^{E}-1}{\sigma_i^{E}}}\right)^{\frac{\sigma_i^{E}}{\sigma_i^{E}-1}}$$

Eq. (A.5) - $\mathrm{PE_i}$ {composite input COAL + Hydrocarbons (HYDRO)}

$$PE_i = \alpha_{iPE}\left(a_{iPE}COAL_i^{\frac{\sigma_i^{PE}-1}{\sigma_i^{PE}}} + (1-a_{iPE})HYDRO_i^{\frac{\sigma_i^{PE}-1}{\sigma_i^{PE}}}\right)^{\frac{\sigma_i^{PE}}{\sigma_i^{PE}-1}}$$

Eq. (A.6) - $\mathrm{HYDRO_i}$ {composite input Refined oil products (REF) + Natural Gas (GAS)}

$$HYDRO_i = \alpha_{iPET}\left(a_{iPET}REF_i^{\frac{\sigma_i^{PET}-1}{\sigma_i^{PET}}} + (1-a_{iPET})GAS_i^{\frac{\sigma_i^{PET}-1}{\sigma_i^{PET}}}\right)^{\frac{\sigma_i^{PET}}{\sigma_i^{PET}-1}}$$

Electricity production sector

Eq. (A.7) - Composite of ELECTRICITY (aggregate of n generation technologies)

$$ELECTRICITY = \alpha_{TECH}\left(\sum\nolimits_{t=1}^{n} s_t ELECT_t^{\frac{\sigma^{TECH}-1}{\sigma^{TECH}}}\right)^{\frac{\sigma^{TECH}}{\sigma^{TECH}-1}}, \sum\nolimits_{t=1}^{n} s_t = 1$$

Eq. (A.8) - Output from technology t {KLE + intermediate inputs ($\mathrm{D_{it}}$)}

$$ELECT_t = \alpha_t\left(a_t KLE_t^{\frac{\sigma_t^{M}-1}{\sigma_t^{M}}} + \sum\nolimits_{j=1}^{n} b_{jt}\left(D_{tj}\right)^{\frac{\sigma_t^{M}-1}{\sigma_t^{M}}}\right)^{\frac{\sigma_t^{M}}{\sigma_t^{M}-1}}, \sum\nolimits_{j=1}^{n} b_{jt} = (1-a_t)$$

Eq. (A.9) – $\mathrm{KLE_t}$ {composite input KL + Energy (E)}

$$KLE_t = \alpha_t\left(a_t KL_t^{\frac{\sigma_t^{KLE}-1}{\sigma_t^{KLE}}} + (1-a_t)E_t^{\frac{\sigma_t^{KLE}-1}{\sigma_t^{KLE}}}\right)^{\frac{\sigma_t^{KLE}}{\sigma_t^{KLE}-1}}$$

Eq. (A.10) – $\mathrm{KL_t}$ {composite input capital (K) + labour (L)}

$$KL_t = \alpha_{tKL}\left(a_{tKL}L_t^{\frac{\sigma_t^{KL}-1}{\sigma_t^{KL}}} + (1-a_{tKL})K_t^{\frac{\sigma_t^{KL}-1}{\sigma_t^{KL}}}\right)^{\frac{\sigma_t^{KL}}{\sigma_t^{KL}-1}}$$

Foreign trade

Eq. (A.11) - Armington nest for total supply {Domestic output (OUTPUT) + Imports (IMP)}

$$A_i = \lambda_i\left(b_i Output_i^{\frac{\sigma_i^{A}-1}{\sigma_i^{A}}} + (1-b_i)IMP_i^{\frac{\sigma_i^{A}-1}{\sigma_i^{A}}}\right)^{\frac{\sigma_i^{A}}{\sigma_i^{A}-1}}$$

Eq. (A.12) - Armington nest for total demand {Domestic demand (D) + Exports (EXP)}

$$A_i = \gamma_i\left(d_i D_i^{\frac{\sigma_i^{\varepsilon}+1}{\sigma_i^{\varepsilon}}} + (1-d_i)EXP_i^{\frac{\sigma_i^{\varepsilon}+1}{\sigma_i^{\varepsilon}}}\right)^{\frac{\sigma_i^{\varepsilon}}{\sigma_i^{\varepsilon}+1}}$$

Consumption

Eq. (A.13) – Welfare function {Leisure + Consumption (UA)}

$$W = \left(s_{UB}LEISURE^{\frac{\sigma^{UB}-1}{\sigma^{UB}}} + (1 - s_{UB})UA^{\frac{\sigma^{UB}-1}{\sigma^{UB}}}\right)^{\frac{\sigma^{UB}}{\sigma^{UB}-1}}$$

Eq. (A.14) – UA composite good {savings (SAV) + Final consumption (FCHOU)}

$$UA = min\left(\frac{SAV_{CONS}}{s_{UA}}, \frac{FCHOU}{(1 - s_{UA})}\right)$$

Eq. (A.15) – FCHOU {composite good of Energy for home (EHOU) + Energy for transport (FUELOIL) + Non-energy goods (NEG)}.

$$FCHOU = \phi_{FCH}\left(s_{EH}EHOU^{\frac{\sigma^{FCH}-1}{\sigma^{FCH}}} + s_{FH}FUELOIL^{\frac{\sigma^{FCH}-1}{\sigma^{FCH}}} + (1 - s_{EH} - s_{FH})NEG^{\frac{\sigma^{FCH}-1}{\sigma^{FCH}}}\right)^{\frac{\sigma^{FCH}}{\sigma^{FCH}-1.}}$$

Eq. (A.16) – EHOU {composite good of Electricity (ELEC) + Primary energy (PEHOU)}

$$EHOU = \phi_{EH}\left(s_{EH}ELEC_H^{\frac{\sigma^{EH}-1}{\sigma^{EH}}} + (1 - s_{EH})PEHOU^{\frac{\sigma^{EH}-1}{\sigma^{EH}}}\right)^{\frac{\sigma^{EH}}{\sigma^{EH}-1}}$$

Eq. (A.17) – NEG {composite consumption of non-energy goods}
$NEG = \prod_{i=1}^{n} D_{iH}^{SO_i}$, where i $\neq$ energy products
Eq. (A.18) – FEHOU {composite good of Coal + Gas + Refined petroleum products (REF)}

$$FEHOU = \phi_{NEH}\left(s_C COAL_H^{\frac{\sigma^{NEH}-1}{\sigma^{NEH}}} + s_G GAS_H^{\frac{\sigma^{NEH}-1}{\sigma^{NEH}}} + (1 - s_C - s_G)REF_H^{\frac{\sigma^{NEH}-1}{\sigma^{NEH}}}\right)^{\frac{\sigma^{NEH}}{\sigma^{NEH}-1}}$$

Appendix B. Production sectors

Sector	Description
AGR&FOR	Agriculture and forestry
FISHING	Fishing and aquaculture
MIN&EXTRACT_FUELS	Mining of coal; extraction of crude petroleum and natural gas
MIN&QUARR	Other mining and quarrying
FOOD&TOB	Manufacture of food, beverages and tobacco products
TEXTILES	Manufacture of textiles products
LEATHER	Manufacture of leather products
WOOD&CORK	Manufacture of wood and cork products
PAPER&PULP	Manufacture of paper and paper products; printing
REF	Manufacture of coke and refined petroleum products
CHEMICALS	Manufacture of pharmaceutical and chemical products
RUB&PLAST	Manufacture of rubber and plastic products
NONMET_MINER	Manufacture of non-metallic mineral products
METALS	Manufacture of basic metals and metal products
MACH&EQUIP	Manufacture and repair of machinery and equipment
ELEC_EQUIP	Manufacture of electric and electronic products
TRANSP_EQUIP	Manufacture of transport equipment
OTHER_MANUF	Other manufacturing
ELECT	Electricity, steam and air conditioning supply
GAS	Natural gas supply
WATER	Water collection, treatment and supply
CONSTRUCTION	Construction
TRADE	Trade and repair
HORECA	Accommodation and food service activities
TRANSP&COMM	Transport and communications
FIN_SERVICES	Financial and insurance activities
REAL_ESTATE	Real estate and rental activities
PUB_ADMIN	Public administration
EDUCATION	Education
HEALTH	Human health activities
SERVICES	Other professional and personal services

Appendix C. Elasticities of substitution

	Production substitution elasticities					**International trade elasticities**	
	Capital, Labour and Energy	Electricity vs. Fossil fuels	Capital vs. Labour	Coal vs. Refined petroleum products and Gas	Refined petroleum products vs. Gas	Armington substitution between domestic and imports	Armington transformation between domestic and exports
	$\sigma_{KLE}^{(a)}$	$\sigma_{E}^{(b)}$	$\sigma_{KL}^{(c)}$	$\sigma_{COG}^{(b)}$	$\sigma_{OG}^{(b)}$	$\sigma_{A}^{(c)}$	$\sigma_{i}^{E(d)}$
AGR&FOR	0.5	0.3	0.56	0.5	0.5	2.2	3.9
FISHING	0.5	0.3	0.56	0.5	0.5	2.2	3.9
MIN&EXTRACT_FUELS	0.5	0.3	1.26	0.5	0.5	2.8	2.9
MIN&QUARR	0.96	0.3	1.26	0.5	0.5	1.9	2.9
FOOD&TOB	0.5	0.3	1.26	0.5	0.5	2.8	2.9
TEXTILES	0.8	0.3	1.26	0.5	0.5	2.8	2.9
LEATHER	0.8	0.3	1.26	0.5	0.5	2.8	2.9
WOOD&CORK	0.8	0.3	1.26	0.5	0.5	2.8	2.9
PAPER&PULP	0.8	0.3	1.26	0.5	0.5	2.8	2.9
REF	0.5	0.3	1.12	0.5	0.5	2.8	2.9
CHEMICALS	0.96	0.3	1.26	0.5	0.5	1.9	2.9
RUB&PLAST	0.8	0.3	1.26	0.5	0.5	2.8	2.9
NONMET_MINER	0.96	0.3	1.26	0.5	0.5	1.9	2.9
METALS	0.8	0.3	1.26	0.5	0.5	2.8	2.9
MACH&EQUIP	0.8	0.3	1.26	0.5	0.5	2.8	2.9
ELEC_EQUIP	0.8	0.3	1.26	0.5	0.5	2.8	2.9
TRANSP_EQUIP	0.8	0.3	1.26	0.5	0.5	2.8	2.9
OTHER_MANUF	0.96	0.3	1.26	0.5	0.5	1.9	2.9
ELECT	0.5	0.3	1.26	0.5	0.5	2.8	2.9
GAS	0.5	0.3	1.12	0.5	0.5	2.8	2.9
WATER	0.5	0.3	1.26	0.5	0.5	2.8	2.9
CONSTRUCTION	0.5	0.3	1.4	0.5	0.5	1.9	0.7
TRADE	0.5	0.3	1.68	0.5	0.5	1.9	0.7
HORECA	0.5	0.3	1.68	0.5	0.5	1.9	0.7
TRANSP&COMM	0.5	0.3	1.68	0.5	0.5	1.9	0.7
FIN_SERVICES	0.5	0.3	1.68	0.5	0.5	1.9	0.7
REAL_ESTATE	0.5	0.3	1.68	0.5	0.5	1.9	0.7
PUB_ADMIN	0.5	0.3	1.68	0.5	0.5	1.9	0.7
EDUCATION	0.5	0.3	1.68	0.5	0.5	1.9	0.7
HEALTH	0.5	0.3	1.68	0.5	0.5	1.9	0.7
SERVICES	0.5	0.3	1.68	0.5	0.5	1.9	0.7
Final demand substitution elasticities							
Consumption vs. Leisure*						σ_{LC}	1.45
Consumption of energy for transport, energy for home and non-energy goods$^{(e)}$						σ_{EOG}	0.1
Consumption of electricity vs. fossil energy products$^{(e)}$						σ_{EH}	1.5
Consumption of fossil energy products$^{(e)}$						σ_{FF}	1
Electricity sector substitution elasticities							
Between generation technologies$^{(f)}$						σ_{TECH}	10
Between intermediate goods and KLE aggregate$^{(g)}$						σ_{M}	0.2
Between capital, labor and energy$^{(g)}$						σ_{KLE}	0.25
Between capital and labor$^{(g)}$						σ_{KL}	1.26

Source: (a) Kemfert and Welsch, 2000; (b) Böhringer et al., 1998; (c) Hertel, 1997; (d) Melo and Tarr, 1992; (e) Labandeira et al., 2009; (f) Wing, 2006; (g) EC, 2013.
Note: *σ_{LC} was calibrated so that the model reproduced the uncompensated labor supply elasticity of 0.4 available in literature (see Labandeira et al., 2009).

Appendix D. Elasticities of substitution used in sensitivity analysis

	$\sigma_{KEL}^{(a)}$	$\sigma_{E}^{(b)}$	$\sigma_{KL}^{(a)}$	$\sigma_{COG}^{(b)}$	$\sigma_{OG}^{(b)}$	$\sigma_{A}^{(c)}$	$\sigma_{i}^{E(c)}$
AGR&FOR	0.516	0.16	0.26	0.07	0.25	2.5	1.25
FISHING	0.516	0.16	0.2	0.07	0.25	2.5	1.25
MIN&EXTRACT_FUELS	0.553	0.16	0.2	0.07	0.25	10.4	5.2
MIN&QUARR	0.553	0.16	0.2	0.07	0.25	5.90	2.95
FOOD&TOB	0.395	0.16	1.12	0.07	0.25	2.30	1.15
TEXTILES	0.637	0.16	1.26	0.07	0.25	7.50	3.75
LEATHER	0.637	0.16	1.26	0.07	0.25	7.50	3.75
WOOD&CORK	0.456	0.16	1.26	0.07	0.25	7.50	3.75
PAPER&PULP	0.211	0.16	1.26	0.07	0.25	5.90	2.95
REF	0.256	0.16	1.26	0.07	0.25	4.20	2.10
CHEMICALS	0	0.16	1.26	0.07	0.25	6.60	3.30
RUB&PLAST	0	0.16	1.26	0.07	0.25	6.60	3.30
NONMET_MINER	0.411	0.16	1.26	0.07	0.25	5.90	2.95
METALS	0.644	0.16	1.26	0.07	0.25	7.50	3.75
MACH&EQUIP	0.292	0.16	1.26	0.07	0.25	8.10	4.05
ELEC_EQUIP	0.524	0.16	1.26	0.07	0.25	8.80	4.40
TRANSP_EQUIP	0.519	0.16	1.26	0.07	0.25	8.60	4.30
OTHER_MANUF	0.529	0.16	1.26	0.07	0.25	7.50	3.75
ELECT	0.256	0.16	1.26	0.07	0.25	5.60	2.80
GAS	0.256	0.16	1.26	0.07	0.25	5.60	2.80

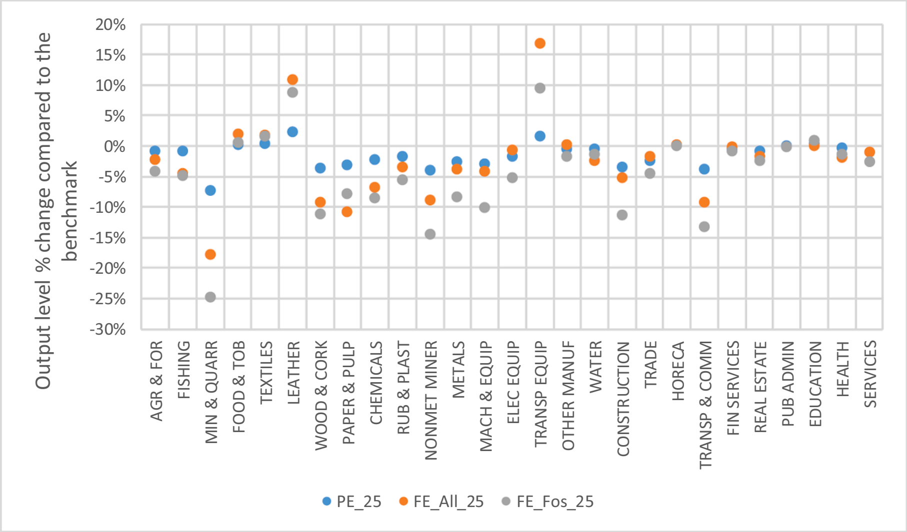
(continued on next page)

(*continued*)

	$\sigma_{KEL}^{(a)}$	$\sigma_{E}^{(b)}$	$\sigma_{KL}^{(a)}$	$\sigma_{COG}^{(b)}$	$\sigma_{OG}^{(b)}$	$\sigma_{A}^{(c)}$	$\sigma_{i}^{E(c)}$
WATER	0.256	0.16	1.26	0.07	0.25	5.60	2.80
CONSTRUCTION	0.529	0.16	1.40	0.07	0.25	3.80	1.90
TRADE	0.784	0.16	1.68	0.07	0.25	3.80	1.90
HORECA	0.784	0.16	1.26	0.07	0.25	3.80	1.90
TRANSP&COMM	0.281	0.16	1.26	0.07	0.25	3.80	1.90
FIN_SERVICES	0.32	0.16	1.26	0.07	0.25	3.80	1.90
REAL_ESTATE	0.32	0.16	1.26	0.07	0.25	3.80	1.90
PUB_ADMIN	0.32	0.16	1.26	0.07	0.25	3.80	1.90
EDUCATION	0.32	0.16	1.26	0.07	0.25	3.80	1.90
HEALTH	0.32	0.16	1.26	0.07	0.25	3.80	1.90
SERVICES	0.784	0.16	1.26	0.07	0.25	3.80	1.90

Source: (a) Okagawa and Ban, 2008; (b) Aguiar et al., 2016; (c) EC, 2013.

Appendix E. Sectoral impacts of energy saving targets' scenarios aiming a 25% reduction in energy consumption on output levels of non-energy sectors



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