The Role of electricity in the decarbonization of the Portuguese economy

FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE NOVA DE LISBOA

WILLIAM & MARY
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SUMMARY REPORT

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Key Findings

Introduction

1. The latest official Portuguese report on greenhouse gas emissions (GHG) (APA, 2017) indicates that net emissions of greenhouse gases (i.e. including the contribution of land use, land-use change and forestry) in Portugal in 2015 are 1.58% lower than 1990 levels. Current GHG emissions amount to 5.8 tCO_2e per capita. GHG emissions from energy and industrial processes, however, have increased 18% and account for 80% of total emissions in Portugal.

2. The Paris climate agreement aims for carbon neutrality by the middle of the century. Given 2015 GHG sequestration levels from land use, land-use change and forestry activities, total GHG emissions in Portugal will need to be reduced from 68.7 $MtCO_2e$ in 2015 to 8.5 $MtCO_2e$ in 2050 (i.e. less than 1 tCO_2e per capita). To meet these goals, Portugal faces the challenge of reducing its GHG emissions by 87% in the next 35 years. The energy sector, and the power sector in particular, will play a major role in this path towards lower GHG emissions.

3. An integrated technological based modelling exercise up to 2050, supported by TIMES_PT model, was performed over the Portuguese energy system to assess the cost-effectiveness of GHG emissions reduction options, (i) with no reduction target imposed, and (ii) by imposing decarbonization targets of 50%, 60%, 75% and 85% in 2050, relative to GHG emissions level in 1990. Additionally, a set of electricity consumption targets (40%, 50%, 70%) was imposed to assess the cost-effectiveness of energy technology options, both supply and demand, and how decarbonization would be induced. The energy technologies database supporting TIMES_PT modelling was fully updated (technical and economic parameters) to fully accommodate the state-of-the-art information.

4. The macroeconomic, budgetary, distributional, and environmental impacts of energy and environmental policies are examined here using a dynamic, multi-sector, general equilibrium model of the Portuguese economy. We examine the effects of a carbon tax with the technical capacity to reduce emissions by 60% in 2050, relative to 1990 levels. We first consider the potential for the tax revenues generated by the tax on carbon to be directed towards debt consolidation efforts. We further consider alternative indirect tax instruments, including broader energy and consumption taxes, capable of generating the same level of revenue for the public sector. Finally, we consider various revenue recycling mechanisms, including reductions to the personal income tax, corporate income tax, value added tax and financing for investment tax credits together with mixed strategies along these different tax margins together with energy efficiency improvements. The DGEP model was greatly expanded to accommodate five income groups and thirteen production sectors as well as to incorporate up-to-date statistical information.

Technological cost-effectiveness of power technologies to decarbonise the portuguese energy system

5. In the absence of additional measures to promote decarbonization in Portugal, an increase in the use of renewable energy of up to 34% of final energy consumption is cost-effective; together with the cost -effective adoption of electric-vehicles absent any policy intervention, the increased share for renewable energy and the adoption of electric vehicles contribute to a significant decarbonization of the energy system in 2050 (a 38% reduction in GHG emissions relative to 1990 levels).

6. The drivers for decarbonization vary with the mitigation target. For a 50% reduction in energy-related GHG emissions in 2050 relative to 1990 levels, the principal driver of decarbonization is the cost-effectiveness of renewable energy in the power sector. Stricter emissions reduction goals of 60% require the decarbonization of consumption but with no significant increase in electricity consumption. GHG reductions greater than 75% require a massive electrification of end use consumption based almost exclusively on renewables. In each scenario, energy efficiency improvements also contributes to the reduction in emissions.

7. The marginal cost of GHG reductions in 2030 for the Portuguese energy system is very similar under the three more stringent mitigation targets, between €33-€35/tCO_2. More notable differences in the marginal cost of CO_2 reductions in 2050 are apparent: a 60% reduction in emissions implies a marginal cost of €183/tCO_2 (in line with similar technological based studies, e.g. PRIMES, or EU-TIMES models), a 75% reduction implies a marginal cost of €411/tCO_2 and a 85% reduction implies a marginal cost of €2930/tCO_2. Although technologically feasible, the marginal cost for decarbonization levels greater than 75% indicates that these goals are not economically viable under the assumptions of this modelling exercise.

8. The cost-effectiveness of selected electricity technologies (e.g., heat pumps, electric vehicles) is indicative of the technological potential for increasing electrification of the Portuguese energy system to up to 30% of total final energy consumption in 2030 (vis-à-vis the current share of 26%), independent of the level of the mitigation target adopted. In the long-term (2050), the degree of electrification depends on the mitigation goal: from 36% of total final energy consumption under the 60% reduction target to 51% under the 85% reduction goal (compared to 34% in the reference scenario).

9. Renewable energy plays a dominant role in electricity generation without additional mitigation policies beyond those in place through 2020. The renewable energy share in electricity generation increases from 60% of generation in 2020, to 68% in 2030 and up to 91% in 2050. Successively more ambitious decarbonization targets drive the power system to an increasing renewable energy share of up to 98% in 2050. Hydropower, onshore wind and solar PV are the most cost-effective technological options, with the first two reaching their maximum technical potential. Offshore wind and Concentrated Solar Power emerge as a cost-effective option in 2050 under stringent mitigation targets.

10. Private passenger transport shows the greatest degree of electrification in 2030 and 2050 due to the cost-effectiveness of adopting electric vehicles. On the other hand, solar thermal technologies for water heating and natural gas for cooking are significant competitors to electric technologies in buildings.

11. Under stringent mitigation targets, electricity use in residential, services and industry will increase significantly in the long-term, reaching 58%, 83% and 45% of their total final energy consumption, respectively (versus the current 41%, 74% and 29%).

12. Electrification targets of 40 to 70% in total final energy consumption by 2050 will induce a modest decarbonization of at most 50% in 2050 relative to 1990 levels. Energy efficiency options are key in all sectors and renewables play an important role in power generation, though a less important role than under decarbonization targets. A maximum of 66% |86% of renewable power is likely to occur in 2030|2050 in the 40% of electricity scenario.

13. Under the more extreme electrification target (70% of final energy consumption) and with the maximum technical potential for hydro, onshore wind and centralized PV met, offshore wind appears as a cost-effective technology.

14. Decarbonization goals induce an increase in the electrification of final energy consumption. An increase in electrification in final energy use alone, however, in the absence of a carbon mitigation framework, does not induce any significant decarbonization, beyond the reference case.

15. The TIMES_PT model optimizes the energy system based on cost-effectiveness, minimizing the costs of the whole energy system, with perfect foresight. It does not consider budget constraints or demand responses to prices and income. The results provide insights with respect to the technologies that will likely play an important role in the decarbonization of the energy system. The TIMES model results provide a wide variety of cost-effective winning strategies to achieve a 60% reduction in greenhouse gas emissions relative to the 1990 levels by 2050.

Macroeconomic effects of the decarbonization of the portuguese energy system

16. The TIMES_PT results provide a wide variety of measures within a cost-effective strategy to achieve by 2050 a 60% reduction in CO_2 emissions relative to 1990 levels. The shadow prices of the emissions constraint reflect the marginal costs of CO_2 reductions and are modelled as a carbon tax in the DGEP model in order to identify the economic, budgetary and distributional effects of decarbonization policies and to highlight the economic mechanisms underlying the transition to a low carbon economy. The carbon tax considered increases from its current level of 5 euros per ton of CO_2 to 183 euros per ton by 2050. The corresponding carbon tax revenues grows from 0.1% to 2.5% of the 2015 GDP, between 2020 and 2050.

17. The DGEP model results indicate that a carbon tax designed to meet the 60% reduction in emissions in 2050 with revenues reverting to the public budget would lead to adverse economic effects in terms of GDP, private consumption and investment and a deterioration of the trade balance. In addition, the labor market effects of this policy would be negative.

18. A tax on carbon dioxide emissions would be regressive and thereby produce undesirable distributional effects. The welfare effects of the tax on carbon are larger for lower income households than for higher income households which raises concerns about social justice emerging from these policies. These negative distributional effects are driven by labor supply responses, lower after-tax incomes and higher consumer prices.

19. The carbon tax would significantly improve the public budgetary situation. This is to be expected because the proceeds from the tax are directed towards the public account by design.

20. The tax is effective in reducing CO_2 emissions and allows for a substantial reduction in emissions. The underlying economic mechanisms, however, suggest a more conservative reduction in emissions than that implied by the TIMES_PT model. The more limited efficacy of the tax in the context of the economic system stems from a greater reliance on output reductions to reduce emissions relative to changes to process and activities given the substitution possibilities for carbon intensive goods and services for both households and firms and the electrification options that are technological feasible within the scope of the TIMES_PT model.

21. The carbon tax provides a direct incentive for reducing emissions that is superior to a more general tax on energy and on consumer goods as a strategy for reducing emissions. As two alternatives to a simple tax on carbon we consider an increase in the tax on energy products and the value added tax that generates the same level of revenue. The additional tax revenues is allocated to the general public sector account. In both alternative cases, the economic effects are substantially smaller, which is just a reflection of a much less effective policy in reducing emissions. Clearly, a carbon tax, being a much more focused instrument, is much more effective in curtailing emissions.

22. The negative economic and distributional effects of a carbon tax motivate the search for tax reforms that can address these adverse effects while reaching the desired environmental objectives. In this more comprehensive tax reform, the carbon tax revenues are allocated to reducing distortions at the major tax margins of the Portuguese tax system, personal and corporate income taxes and value added taxes, together with energy efficiency objectives.

23. Reductions to the personal income tax (PIT) can be designed to promote progressive policy outcomes. Reform to the value added tax (VAT) can also be used to address the adverse distributional effects of the carbon tax. Reductions to the corporate income tax (CIT) and financing for an investment tax credit (ITC) margins are particularly effective in reducing the adverse economic effects of the policy.

24. We examine the potential for mixed recycling strategies to achieve a triple dividend: an improvement in environmental quality, positive economic outcomes and a contribution towards social justice. We first consider a direct tax channel, a combination of reductions in the PIT and the CIT; second, an indirect tax channel, a combination of reductions in the VAT and an increase in the ITC; and, third, a mixed channel with reductions in the PIT and an increase in the ITC. We conduct grid searches to identify the mixed recycling strategies capable of producing the most desirable outcomes. In each case, part of the carbon tax revenues are used to promote the adoption of energy efficiency technologies through selected VAT reductions and PIT credits for energy efficiency improvements for households and CIT financing and ITC credits for energy efficiency improvements for firms.

25. A balanced 50/50 mixed revenue recycling policy yield all of the desirable results: economic growth and job creation, progressive distributional outcomes, and a reduction in CO_2 emissions.

26. These mixed recycling strategies provide for a comprehensive package of policy instruments capable of addressing the environmental, social and economic dimensions of policy concerns facing the country and provide mechanisms for reducing CO_2 emissions by 60% relative to 1990 levels by 2050.

1. Introduction

This report provides a non-technical summary for the role of electricity in the decarbonization of the Portuguese economy.

Two main motivating questions guided this study:

1. What is the extent to which electricity can contribute to the decarbonization of the Portuguese energy sector?
2. What are the economic, budgetary and distributional impacts of policies to support the decarbonization of the Portuguese economy?

These questions are extremely relevant within the context of the Paris Agreement which requires deep reductions in greenhouse gas (GHG) emissions to contribute towards a global carbon neutral balance by middle of the 21rst century. Energy efficiency improvements together with the increased reliance on clean and renewable energy sources are cost-effective strategies with the technical capacity to achieve deep cuts in GHG emissions (see, for example, Berst, 2008; Williams, et al. 2012, EURELETRIC, 2017 study and OECD/IEA and IRENA 2017 among many others). Multiple pathways exist to achieve substantial reductions in emissions using existing commercial or near-commercial technologies, with the technical capacity to reduce GHG to 80% below 1990 levels by 2050. Commonly highlighted strategies focus on investments in energy efficiency, the decarbonization of electricity generation, electrification of most end uses, and switching to fuels with a lower carbon content in the remaining end uses to achieve deep reductions in emissions. In particular, the European Roadmap for a Low Carbon Economy in 2050 (EC, 2011) showed the feasibility of reducing GHG by 80% in 2050 in comparison with 1990, mostly based on the deep decarbonization of the power sector and the electrification of final energy uses of energy.

The cost-effectiveness of these decarbonization strategies depends on the characteristics of the energy system and how these characteristics can be expected to evolve. Generally, the decarbonization of the electric power industry through the adoption of renewable energy sources (RES) coupled with an increased electrification of energy demand and ambitious energy efficiency improvements has emerged as a robust strategy capable of producing deep reductions in greenhouse gas emissions. A technical assessment of the Portuguese energy system decarbonization, conducted in 2011, demonstrated the feasibility of a cost-effective reduction in GHG emissions of 70% (Seixas et al, 2011). These reductions in GHG emissions are important beyond their contribution towards combating climate change but also provide correlated benefits in terms of improvements in air quality and may contribute towards positive trade outcomes for the energy sector. These reductions, though ambitious, are insufficient for Portugal to become carbon neutral as required by agreement at the COP22 in Marrakesh. This goal would require an 87% reduction in emissions by 2050 relative to 1990 levels, assuming the same level of sequestration of CO_2 emissions from the land use, land-use change and forestry activities as observed in 2015. This policy objective would require a reduction in emissions in Portugal from 68,7 $MtCO_2e$ in 2015 to 8.5 $MtCO_2e$ around 2050.

The Portuguese energy system provides a particularly interesting case study for significant electrification as a strategy towards a deep decarbonization because:

1. the power system is currently based on 61% of RES installed capacity and delivering higher volumes of electricity may be very challenging;
2. electricity consumption per capita is very low (circa 15.9 GJ/inhabitant) compared to other EU countries (e.g. 22.6 GJ/inhabitant in Germany or 18 GJ/inhabitant in Spain in 2015 (PORDATA, 2016)), meaning that there is a significant room to expand its use in all economic sectors (electricity represented 28% of the final energy balance in 2016 (DGEG, 2017)), and
3. there is a political commitment for a carbon neutral economy by 2050, requiring additional information to support deep decarbonization goals.

The goal of the study is thus to assess the role of the electricity on the deep decarbonization of the national energy system, i.e. at what extent, when and in what activities electricity may portray a key role in decarbonizing the Portuguese energy system up to 2050, looking both at its subsequent technological and macro-economic implications.

2. Modelling the role of electricity for decarbonization

2.1. Integrated Modelling of Economic and Energy System

The analysis of the role of the electricity in the decarbonization of the Portuguese economy is based on a soft-link between the energy technology systems model TIMES_PT and the dynamic multi-sector general equilibrium model of the Portuguese economy, DGEP. The two models bring together two complementary approaches to energy and climate policy analysis, an energy systems approach and an economic approach, providing a comprehensive view of the issues at stake.

2.2. TIMES - Energy Technology Model

TIMES_PT is a peer-reviewed model for the Portuguese energy system, in use for more than 15 years (Simões et al, 2008, Gouveia et al., 2012, Fortes et al., 2014, Simões et al., 2014, 2015, Fortes et al., 2015), and has been used to support public policy (Seixas et al., 2010; Seixas et al., 2012). The TIMES _PT model is based on the TIMES (The Integrated MARKAL-EFOM system) linear optimization energy model generator developed by ETSAP-IEA. The ultimate objective of the model is to minimize total energy system cost in order to meet energy services demand subject to technological, physical and policy constraints. To this end, the model makes simultaneous decisions regarding technology investment, primary energy supply and energy trade (Loulou et al. 2005). The TIMES_PT model considers the entire Portuguese energy system, activities and processes including energy supply (production, imports and exports), transformation (power and heat production), distribution and end-use energy demand in industry, residential, services, agriculture and transport (Fortes et al., 2015) in 5-year time steps from 2005 to 2050. The model is supported by a highly-detailed technology database, containing more than two thousand supply and demand technologies (both current and emergent) characterized by current tecno-economic information and their respective evolution over time (e.g., investment, operation and maintenance costs, efficiency, life time, availability). TIMES_PT also considers economic and physical information with respect to the energy resources available to satisfy demand, including imports, and Portugal's RES potentials, which are estimated from national studies and validated by national experts (Seixas et al., 2012).

For the purpose of this study, the following improvements were included in the model: (i) a thorough update of the energy technologies database (technical and economic parameters), (ii) the updated RES potentials for solar PV and concentrated solar power (CSP) (13.4 GW for solar PV roof size and a combined potential of 12.0 GW for both CSP and solar PV plant size); (iii) the modelling of the electricity transmission and distribution networks costs as fixed costs, instead of variable costs, and (iv) a detailed analysis of the electricity vector per energy service.

The socio-economic development and the respective projections of energy services demand are exogenous driving forces of the whole energy system modelled in TIMES_PT. A socioeconomic scenario which considers an average annual GDP growth of around 1.5% and a population decrease of -0.3% per year from 2020 onwards is assumed for this study, as shown in Figure 1. The import prices for oil, gas and coal are defined in the New Policy Scenario of the World Energy Outlook 2016 (IEA, 2016). Energy price scenarios are consistent across both modeling platforms to allow for a complementary and comparable description of the effects of electrification and decarbonization policies on the energy sector and on the Portuguese economy.

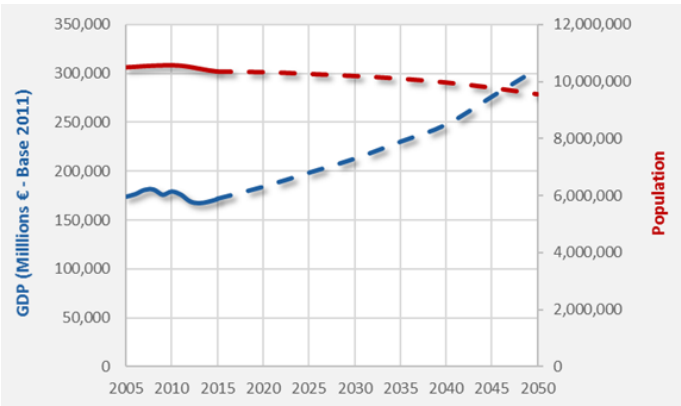


FIGURE 1 | GDP AND POPULATION ASSUMPTIONS

Unless explicitly stated, the scenarios generated by TIMES_PT consider the following common exogenous assumptions: (i) (i) average annual hydrological conditions; (ii) current oil products tax (ISP), road transport tax (IUC), and carbon price of 5€/tCO_2 applied to the EU Emissions Trading System (EU-ETS) sectors (except in the decarbonization scenario); (iii) zero net electricity imports after 2015; (iv) no nuclear energy option; and (v) no new conventional coal power plants option. All the scenarios are supported by the same technological database. Feed-in tariffs for renewable energy sources and energy efficiency targets are not considered. These assumptions permit an assessment of the cost-effectiveness of energy technology options to support ambitious decarbonization targets.

2.3 DGEP – Dynamic General equilibrium model

The economic, budgetary, distributional, and environmental effects of decarbonization policies are further evaluated using a multi-sector, multi-household, dynamic general equilibrium model of the Portuguese economy. This new model builds upon the aggregate dynamic general equilibrium model of the Portuguese economy DGEP. Previous versions of this model are documented in Pereira and Pereira (2012) and have been used to evaluate the impact of tax policy [see Pereira and Rodrigues (2002, 2004)], of public pension reform [see Pereira and Rodrigues (2007)], and more recently of energy and climate policy issues [see Pereira and Pereira (2014a, 2014b, 2016a, 2016b)].

The dynamic multi-sector general equilibrium model of the Portuguese economy incorporates fully dynamic optimization behavior, detailed household accounts, detailed industry accounts, a comprehensive modelling of the public sector activities, and an elaborated description of the energy sectors. We consider a decentralized economy in a dynamic general equilibrium framework. There are four types of agents in the economy: households, firms, the public sector and a foreign sector. All agents and the economy in general face financial constraints that frame their economic choices. All agents are price takers and are assumed to have perfect foresight. With money absent, the model is framed in real terms.

Households and firms implement optimal choices, as appropriate, to maximize their objective functions. Households maximize their intertemporal utilities subject to an equation of motion for financial wealth, thereby generating optimal consumption, labor supply, and savings behaviors. We consider five household income groups defined by quintile of income. Preferences, income, wealth and taxes are household-specific, as are consumption demands, savings, and labor supply.

Firms maximize the net present value of their cash flow, subject to the equation of motion for their capital stock to yield optimal output, labor demand, and investment demand behaviors. We consider thirteen production sectors covering the whole spectrum of economic activity in the country. These include energy producing sectors, such as electricity and petroleum refining, other EU-ETS sectors, such as aviation transportation, wood pulp and paper, chemicals and pharmaceuticals, rubber, plastic and ceramics, and primary metals, as well as non-ETS sectors such as agriculture, basic manufacturing and construction. Production technologies, capital endowments, and taxes are sector-specific, as are output supply, labor demand, energy demand, and investment demand.

The public sector and the foreign sector, in turn, evolve in a way that is determined by the economic conditions, and their respective financial constraints. All economic agents interact through demand and supply mechanisms in different markets: commodity markets, factor markets, and financial markets.

The general market equilibrium is defined by market clearing conditions in product markets, labor markets, financial markets, and the market for investment goods. The product market equilibrium reflects the national income accounting identity and the allocation of the output of each sector of economic activity to various types of expenditure. The total amount of a commodity supplied to the economy, be it produced domestically or imported from abroad, must equal the total end-user demand for the product, including the use of these products as intermediate inputs in production, the demand for private consumption by households, by the public sector, and its use for private investment. The total labor supplied by the different households, adjusted by an unemployment rate that is assumed exogenous and constant, must equal total labor demanded by the different sectors of economic activity. There is only one equilibrium wage rate, although this translates into different household-specific effective wage rates, based on household-specific levels of human capital which differ by income level. Different firms buy shares of the same aggregate labor supply. Implicitly, this means that we do not consider differences in the composition of labor demand among the different sectors of economic activity, in terms of the incorporated human capital levels. Savings by households and the foreign sector must equal the value of domestic investment plus the budget deficit.

The evolution of the economy is described by the optimal and endogenous evolution of the stock variables – five household-specific financial wealth variables and thirteen sector-specific private capital stock variables including wind, solar and hydroelectric renewable energy sources, as well as their respective shadow prices/co-state variables. In addition, the evolution of the stocks of public debt and of the foreign debt act as resource constraints in the overall economy. The endogenous and optimal changes in these stock variables – investment, saving, the budget deficit, and current account deficit – provide the endogenous and optimal link between subsequent time periods. Accordingly, the model can be conceptualized as a large set of nonlinear difference equations, where critical flow variables are optimally determined through optimal control rules.

The intertemporal path for the economy is described by the behavioral equations, by the equations of motion of the stock and shadow price variables, and by the market equilibrium conditions. We define the steady-state growth path as an intertemporal equilibrium trajectory in which all the flow and stock variables grow at the same rate while market prices and shadow prices are constant.

The model is calibrated with data for the period 2005-2014 and stock values for 2015. The calibration of the model is ultimately designed to allow the model to replicate, as its most fundamental base case, a stylized steady state of the economy, as defined by the trends and information contained in the data set. Counterfactual simulations thus allow us to identify marginal effects of any policy or exogenous change, as deviations from the base case.

2.4 Integrated Modelling Economic and Energy Systems for Deep Decarbonization Assessment

The Reference (REF) scenario was defined as a pathway for the energy sector and the economy that explicitly considers the energy and climate policy targets for 2020 with the objective of identifying the role of electricity in the energy system given the expected evolution of the costs and characteristics of the various energy technologies absent further policy objectives.

The energy system and economic models were integrated using a harmonization process designed to ensure that modeling approach provides a complementary and coherent analysis of the energy, environmental, macroeconomic, budgetary and distributional effects of electrification and decarbonization policies in Portugal. The soft-link between the energy technology systems model and the dynamic multi-sector general equilibrium model of the Portuguese economy process is depicted in Figure 2 and is based on key indicators for the energy system: carbon dioxide emissions, final demand for electricity, and share of renewables in the electricity production. The endogenously generated trajectories for these key energy system indicators in 2020, 2030, 2040 and 2050 were iterated under the reference scenario until the difference in the model reference scenario converged to within 10% for each time period under consideration (Table 1). In addition, selected energy drivers generated by TIMES_PT model were adopted by the DGEP model (e.g. energy efficiency), while economic drivers generated by DGEP were used by the TIMES_PT model (e.g. household private consumption).

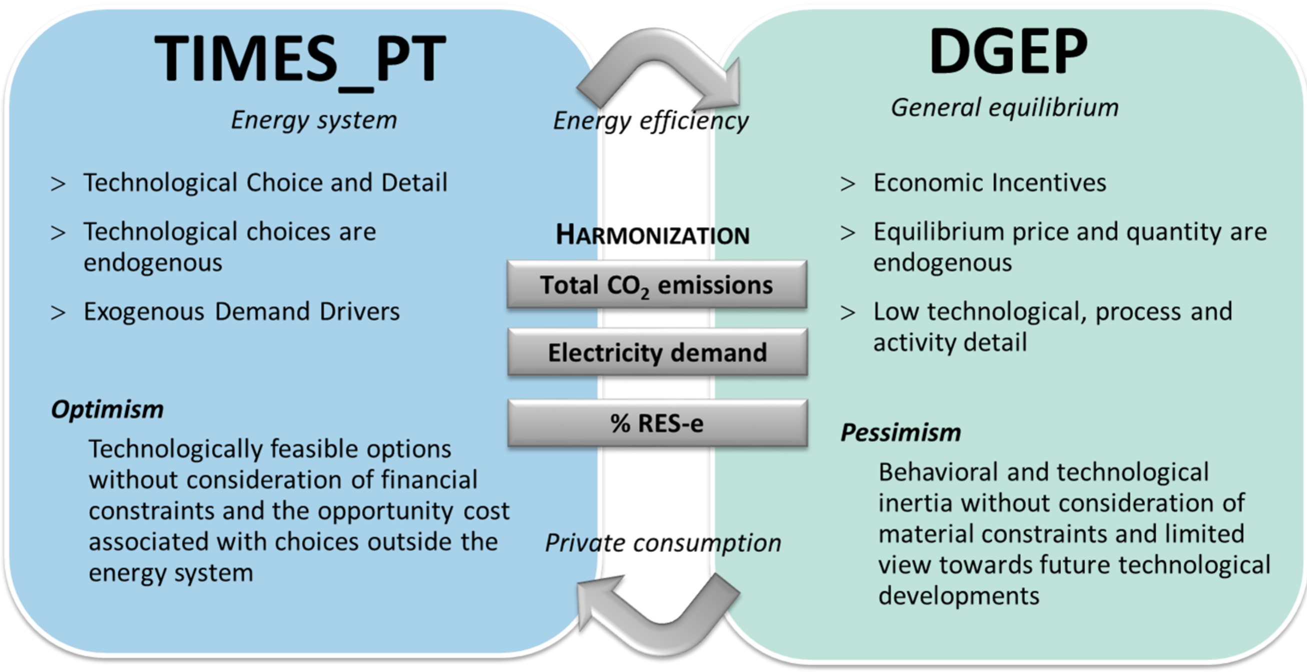


FIGURE 2 | INTEGRATED MODELLING APPROACH

TABLE 1 | OVERVIEW OF THE HARMONIZATION RESULTS (2015 = 100)

	2020	2030	2040	2050
CO_2 EMISSIONS				
TIMES	95.7	84.7	64.0	57.6
DGEP	95.0	89.1	64.5	63.2
Percent. Diff.	0.8	-4.9	-0.8	-8.9
ELECTRICITY – FINAL DEMAND				
TIMES	101.4	109.4	119.0	122.9
DGEP	106.3	121.3	119.2	123.9
Percent. Diff.	-4.7	-9.8	-0.2	-0.8
ELECTRICITY PRODUCTION - RENEWABLES (%)				
TIMES	113.2	126.4	160.4	171.7
DGEP	105.0	114.1	158.5	164.4
Percent. Diff.	7.8	10.8	1.2	4.4

2.5 Modelled scenarios

Several scenarios were evaluated to examine the extent to which electricity will likely contribute to the decarbonization of the Portuguese energy system and the economy (Figure 3). Besides the Reference scenario described in the previous section, two families of counterfactual energy sector scenarios were modelled by the TIMES_PT energy technology model:

i. ***Decarbonization scenarios**:* the price of 5€/tCO_2 applied to EU-ETS sectors, as in REF, was substituted by an overarching cap on GHG energy and industrial processes-related emissions corresponding to a 50%, 60%, 75% and 85% reduction in emissions by 2050 relative to 1990 values (named respectively, CO2-50%, CO2-60%, CO2-75% and CO2-85%). These scenarios allow for an assessment of the role of electricity and its relationship with other final energy carriers in response to diverse CO_2 mitigation targets;

ii. ***Electrification scenarios**:* Targets for the shares of electricity in final consumption of 40%, 50% and 70% (named respectively, ELC40, ELC50 and ELC70). These scenarios allow for an assessment of potential for expanding electricity demand to reduce emissions.

Two families of counterfactual economic scenarios were modeled by the DGEP general equilibrium model:

i. ***Decarbonization scenarios***: Decarbonization strategies based on a carbon tax (1), an energy tax (2), and value added taxation (3). The tax levels are defined in a way that is consistent with the marginal costs of emissions reductions associated with the 60% reduction goal defined by the TIMES model. Each tax policy generates the same revenue for the public sector and the proceeds from these tax instruments are used to finance deficit reduction.

ii. ***Decarbonization scenarios with Environmental Tax Reform***: The carbon tax revenues collected in the previous scenario are recycled to finance changes in four tax margins: reductions in the personal income tax, the corporate income tax, and the value added tax, and an increase in investment tax credits, all combined with incentives for energy efficiency.

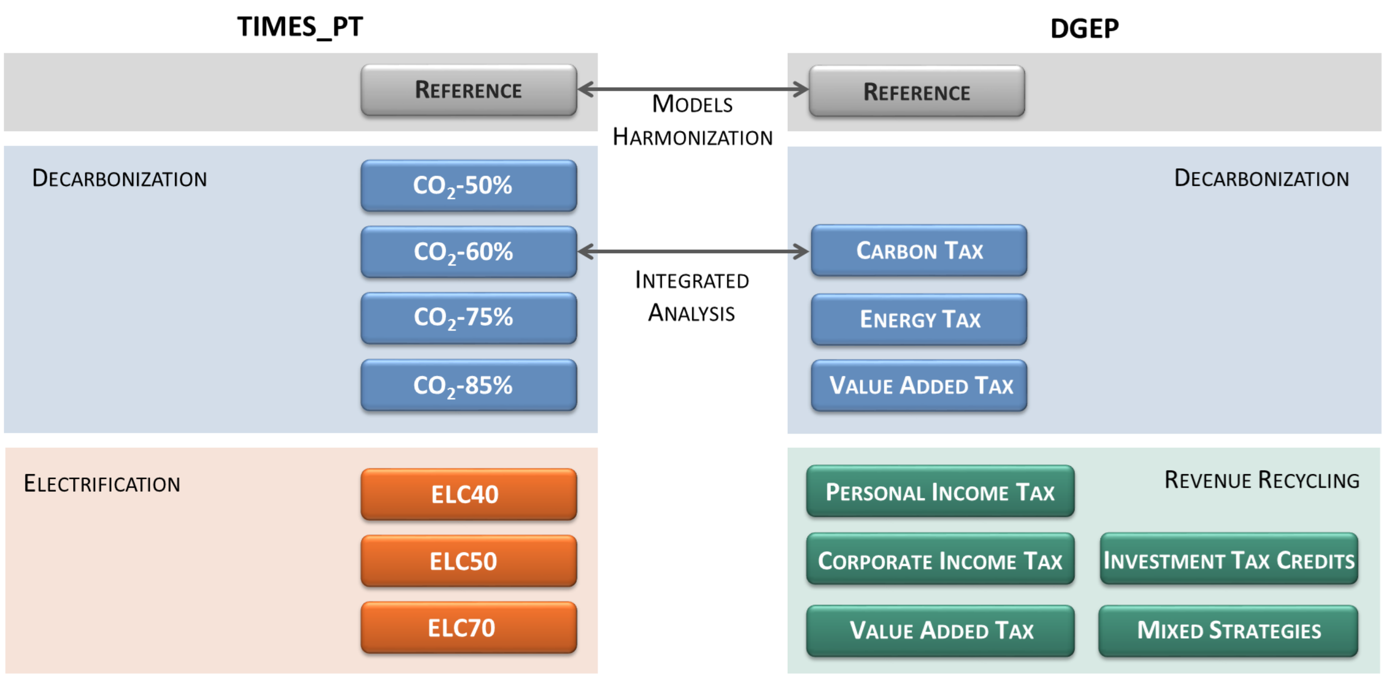


FIGURE 3 | INTEGRATED MODELLING APPROACH

3. What is the role of electricity in decarbonizing the Portuguese economy?

Deep decarbonization goals yield pathways do not have a substantial impact on the share of electricity in final energy consumption in the short-run, by 2030. These objectives, however, lead to longer term changes in the energy sector that support an increased electrification of total final energy consumption by 2050, as depicted in Figure 4. These results indicate that, regardless of the specific mitigation target adopted, we will likely observe an increase in the electrification of the energy system for its current level of 28% of final energy demand in 2016 to near 30% of final energy demand in 2030. In the long term, however, the level of electrification of final energy consumption through 2050 depends, in large part, on the mitigation target adopted: 34% (REF), 36% (CO2-60%), 44% (CO2-75%) and 51% (CO2-85%).

The Reference scenario suggests a substantial decarbonization of the energy system in 2050, along with an increased electrification, absent any significant policy intervention. GHG emissions from energy and industrial processes are expected to fall to levels that are 38% lower than 1990 levels by 2050. This is a substantial reduction from 2015 levels, when GHG emissions were 17% above 1990 levels. This is a very substantial decarbonization of the Portuguese energy system due in large part to cost-effective adoption of renewable energy resources, increases in energy efficiency and the increasing use of electric vehicles. This reference scenario stems from optimal cost-minimizing behavior by individuals within the energy system in which the cost-effective deployment of new energy technologies is rational.

Electrification objectives, without accompanying decarbonization goals, do not contribute to higher rates of decarbonization than those implied by the reference scenario (Figure 5). Renewable electricity and energy efficiency are cost-effective up to an electrification of 40% of total final energy consumption (ELC 40%). For higher shares of electricity, and in the absence of mitigation targets, it is more cost-effective to generate electricity from natural gas plants given the technical potential for electricity generation from competitive renewable sources.

The decarbonization strategies considered yield different mitigation trajectories as can be seen in Figure 6. The marginal cost of CO_2 abatement varies substantially for the different decarbonization goals studied. **Marginal abatement costs[1] vary from 183 €/tCO_2e in 2050 for the 60% emissions reduction target to 2 930 €/tCO_2e for the 85% emissions reduction target** (Table 2). The substantial costs associated with the CO2-85% scenario indicate that the technological portfolio considered, although technologically feasible, may not be an economically viable option. The development and deployment of additional technological options may be required to reduce compliance costs. Some potential carbon reduction technologies not considered here are all-electric heavy trucks, electric kilns in industrial usage and carbon capture and utilization technologies in the cement industry, to name a few.

The **power sector assumes a dominant role in reducing emissions in the reference scenario and in the CO2-50% scenario.** The primary role for the power sector stems from the cost-effectiveness of the renewables options (RES-e) rather than policy objectives. In fact, in 2050 the RES-e share increases up to 91% in the reference scenario without any additional mitigation or energy policy. **It becomes cost-effective for other sectors to contribute to the decarbonization of the energy system with more ambitious GHG emissions targets**. In the CO2-60% scenario, electricity replaces fossil fuels for heating in the commercial sector; In the CO2-75% scenario, residential and transportation sectors begin to contribute towards emissions reduction efforts. In the residential sector, electric boilers and furnaces replace gas boilers and furnaces for heating and solar thermal panels with electric power backup begin to replace gas and LPG boilers for hot water. In the transport sector, a substantial increase in the use of biodiesel in freight transport is cost-effective. **Electric vehicles are cost-effective in the reference scenario** and account for 74% of the passenger travel by car in 2050, increasing to 84% in the CO2-60% scenario, to 90% in the CO2-75% and CO2-85% scenarios. These are upper bounds on electric vehicles deployment.

[1]All the monetary values in this report are expressed in €2011.

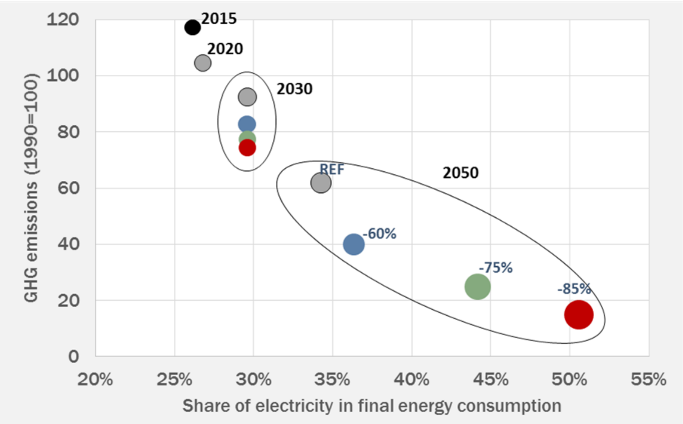


FIGURE 4 | SHARE OF ELECTRICITY IN TOTAL FINAL ENERGY CONSUMPTION AND CORRESPONDING GHG EMISSION MITIGATION FOR DECARBONIZED SCENARIOS IN 2015, 2020, 2030 AND 2050

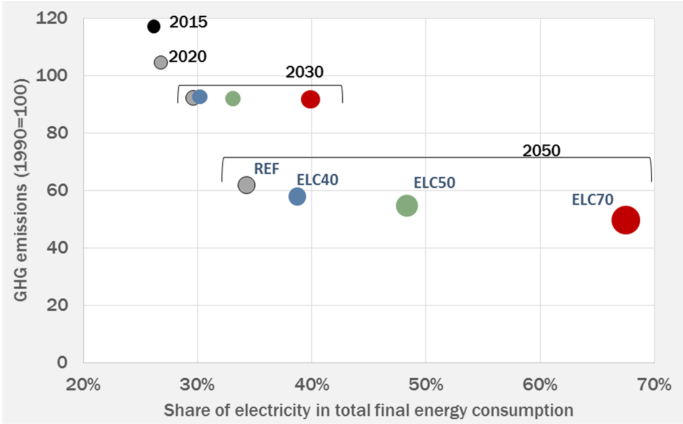


FIGURE 5 | SHARE OF ELECTRICITY IN TOTAL FINAL ENERGY CONSUMPTION AND CORRESPONDING GHG EMISSION MITIGATION FOR THE ELECTRIFICATION SCENARIOS IN 2015, 2020, 2030 AND 2050

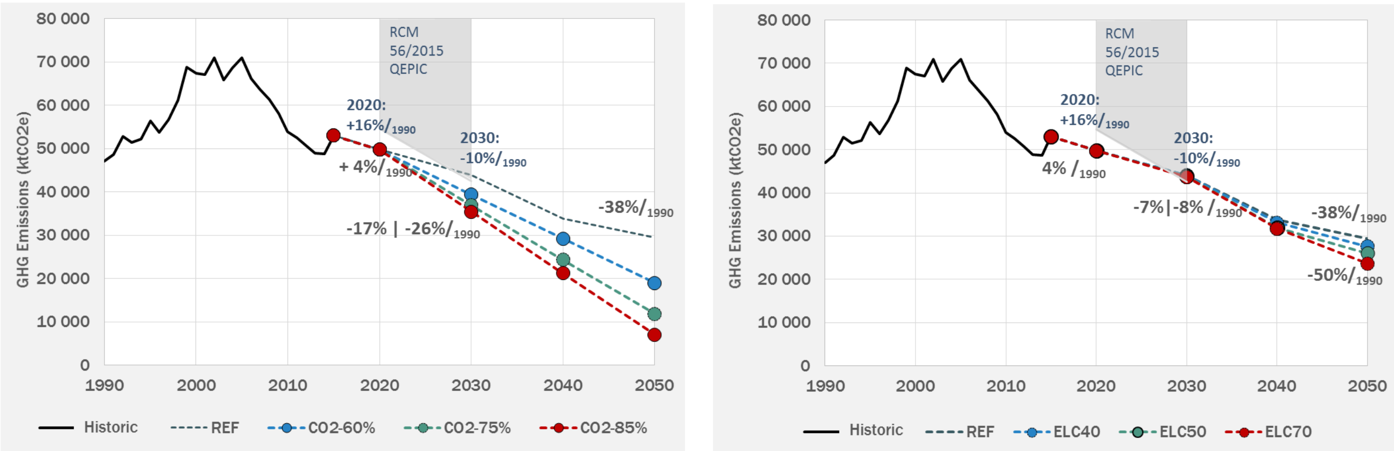


FIGURE 6 | EVOLUTION OF ENERGY RELATED GHG EMISSIONS FROM 1990 TILL 2050 IN THE REF AND DECARBONIZED SCENARIOS (LEFT) AND IN THE REF AND ELECTRIFICATION SCENARIOS (RIGHT). GHG EMISSION VALUES FROM 1990 TILL 2015 ARE HISTORIC. THE 2020 AND 2030 GHG NATIONAL MITIGATION TARGETS (QEPIC) ARE INCLUDED FOR COMPARISON PURPOSES

TABLE 2 | SELECTED INDICATORS FROM THE MODELLED SCENARIOS IN 2030 AND 2050

Scenario/ year	% RES in Final Energy Consumption*		% GHG energy emissions reduction vis-à-vis 1990		% RES electricity		CO_2 marginal abatement cost (€/tCO_2)	
	2030	2050	2030	2050	2030	2050	2030	2050
REF	37%	55%	-8%	-38%	68%	91%	5	5
CO2-50%	39%	65%	-17%	-50%	74%	91%	17	119
CO2-60%	40%	68%	-17%	-60%	76%	92%	33	183
CO2-75%	40%	88%	-23%	-75%	79%	94%	37	411
CO2-85%	41%	95%	-26%	-85%	82%	98%	36	2930
ELC40	37%	59%	-7%	-42%	68%	89%	-	-
ELC60	39%	64%	-8%	-45%	67%	86%	-	-
ELC70	40%	76%	-8%	-50%	66%	86%	-	-

*calculated as in the Directive 28/2009/EC

What is the increase of electricity consumption?

Due to the adoption of cost-effective energy efficiency technological options, the final energy consumption (FEC) is slightly reduced in 2050 in all scenarios from 2015 values, although the increase of energy services we may expect: between -2.8% (in REF) and -7.7% (in CO2-85%). Nonetheless, in all modelled scenarios, the electricity consumption increases both in absolute terms (46 TWh in 2015, to 59 TWh in REF in 2050, 62-82 TWh in 2050 in the decarbonization scenarios, and 64-100 TWh in 2050 in the electrification scenarios), and in relative share for total FEC (Figure 7). We may likely observe an increase of electricity consumption per capita from 4.4 MWh/inhabitant in 2015 to 6.5-8.6 MWh/ inhabitant in the decarbonization scenarios, or up to 6.1-10.5 MWh/inhabitant in the electrification scenarios (Figure 8). In fact, the modelling exercise shows an increase of the share of electricity in FEC in all scenarios from the observed 26% in 2015: 35% in REF in 2050; 35-41% in the decarbonization scenarios; and 39-67% in the electrification scenarios. All end use sectors increase electricity consumption due to high cost-effectiveness of electric technologies, usually more efficient than its competitors, although at a different pace, depending on electrical options available. The sector with highest

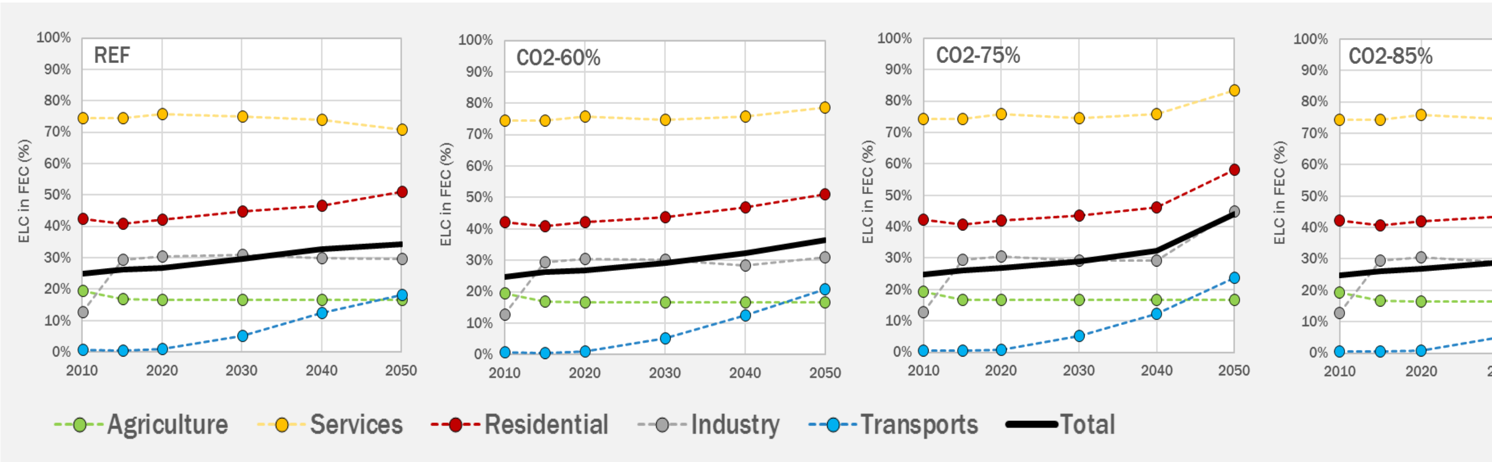


FIGURE 7 | EVOLUTION OF SHARE OF ELETRICITY IN TOTAL FINAL ENERGY CONSUMPTION IN THE DECARBONIZATION AND ELECTRIFICATION SCENARIOS

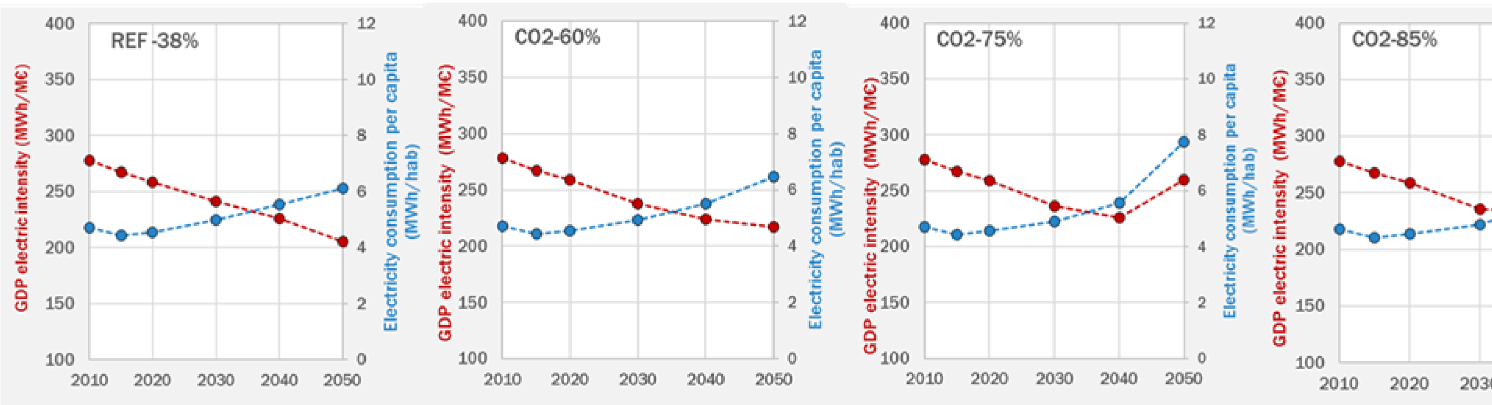


FIGURE 8 | EVOLUTION OF GDP ELECTRIC INTENSITY AND ELECTRICITY CONSUMPTION PER CAPITA IN THE DECARBONIZATION AND ELECTRIFICATION MODELLED SCENA

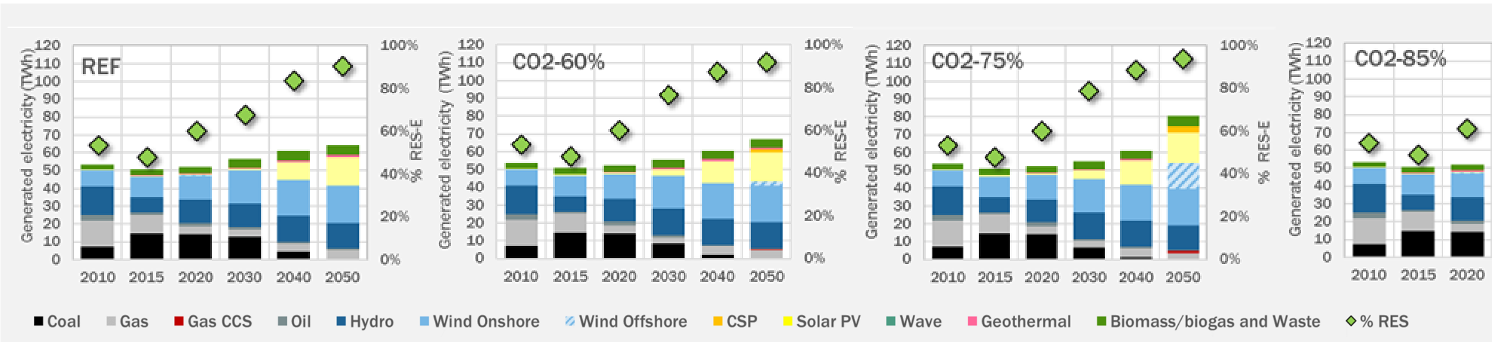
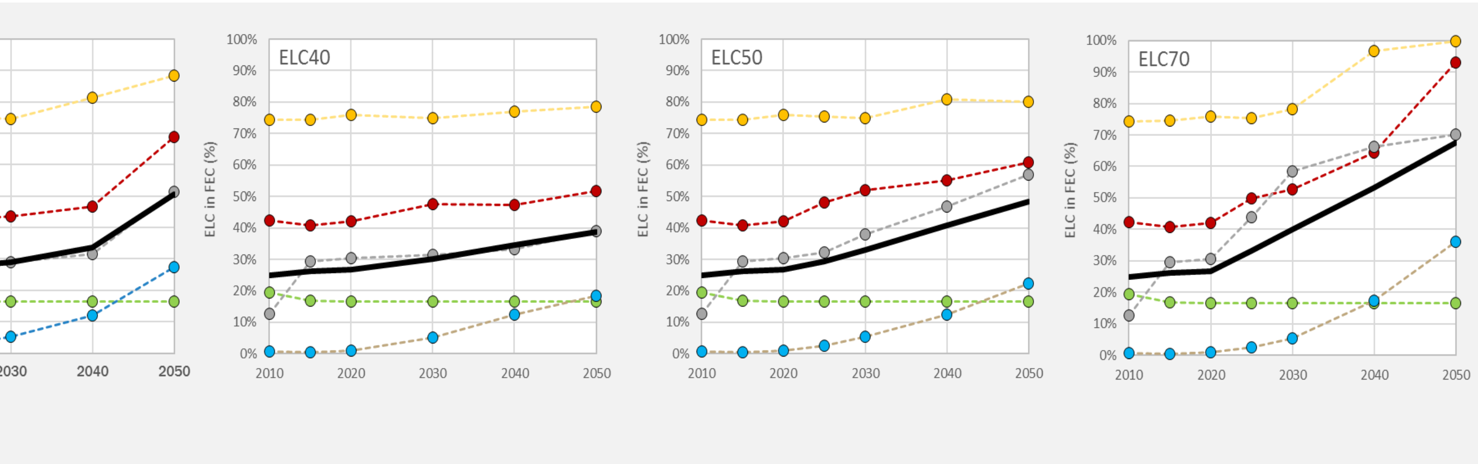
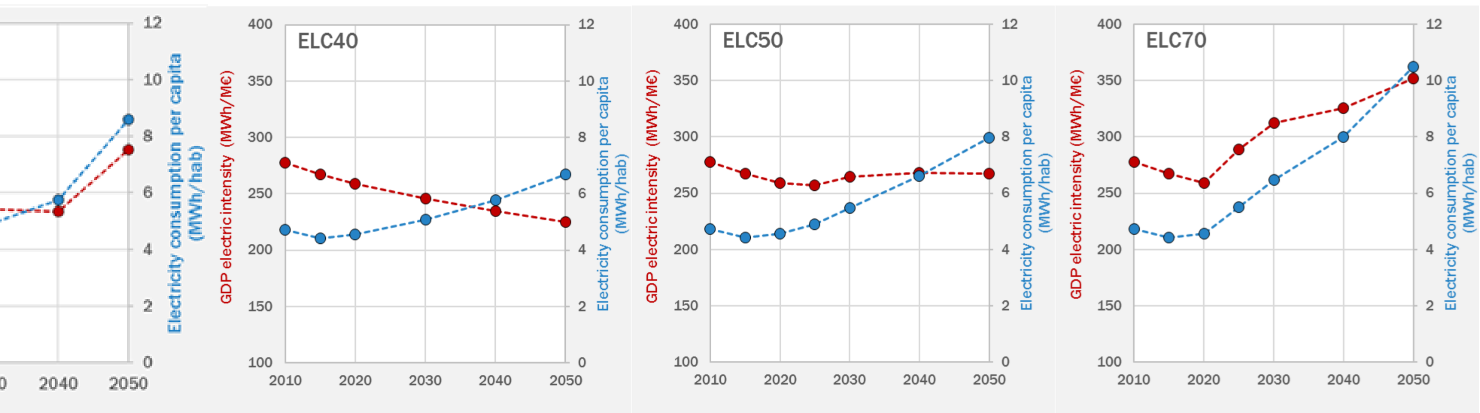


FIGURE 9 | GENERATED ELECTRICITY PER TECHNOLOGY IN THE DECARBONIZATION AND ELECTRIFICATION MODELLED SCENARIOS electricity share is the services, followed by residential buildings, industry and transport. The extreme electrification scenario ELC70 illustrates the maximum possible deployment of electric end-use technologies (almost 70% overall, and almost 100% in the services sector).

The electric intensity of the GDP tends to decrease in all scenarios, since the main driver for decarbonization is energy efficiency, including through electrification. However, for mitigation targets higher than 60%/1990, electric intensity of the GDP increases after 2040, as decarbonization is made through carbon free electricity.

Renewables play a dominant role in electricity generation (Figure 9), even in the absence of a mitigation policy beyond the one in place up to 2020. Under the reference scenario renewable electricity increases from 60% in 2020, to 68% in 2030 up to 91% in 2050. Successive aggressive decarbonization targets conduct the power system to increasing renewable participation up to 98% in 2050. Hydropower, onshore wind and solar PV are the most cost-effective technological options, with the first two reaching the maximum technical potential considered. Offshore wind and CSP emerges as a cost-effective option in 2050 under stringent mitigation targets (i.e., -75% and -85%) associated with higher CO_2 abatement cost.





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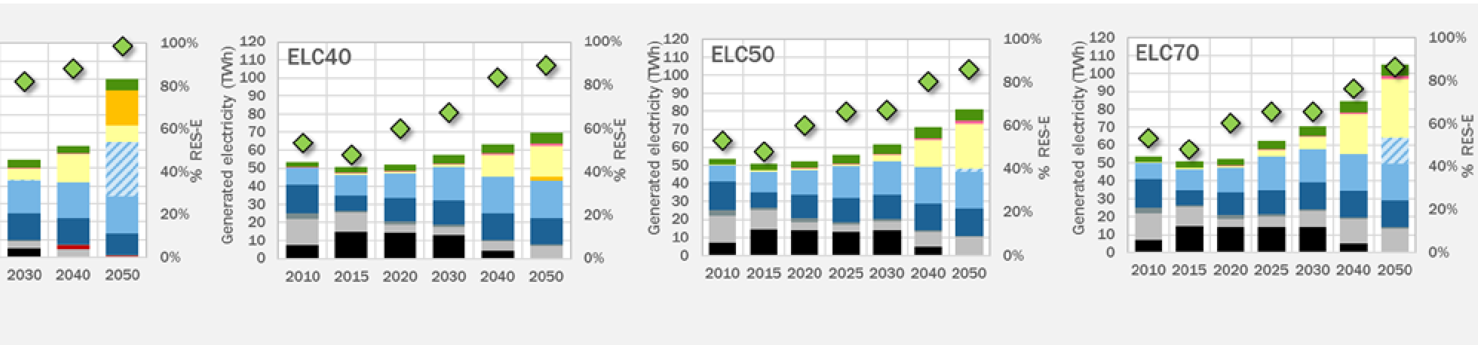

4. What are the macro-economic impacts of decarbonization policies in Portugal?

The **reference scenario** adopted by the TIMES_PT and the DGEP models — the starting point for the analysis of the macroeconomic effects of decarbonization policies — incorporates sizable reduction in CO_2 emissions and advances in electrification and the use of renewable energy sources relative to a business as usual scenario. We start from this reference scenario to define a whole array of **counterfactual scenarios** divided in two groups. First, we consider several decarbonization policies based on a tax on carbon, on a broader-based energy tax and on an increase in the value added tax. Second, we consider a broader environmental tax reform with revenues from the carbon tax being recycled to finance reductions in several distortionary tax margins - personal income tax, corporate income tax, value added taxes as well as increases in investment tax credits, all combined with incentives for energy efficiency improvements. All counterfactual results are presented as percentage deviations from the reference scenario. All results reported here refer to long-term effects in 2050.

The TIMES_PT model provides a wide variety of options within a cost-effective strategy for reducing CO_2 emissions in 2050 by 60% relative to 1990 levels. The shadow price of the emissions constraint defined in the TIMES_PT model for the CO2-60% scenario provides the marginal cost of emissions abatement and is implemented as a tax on carbon dioxide emissions to assess the macro-economic impact of decarbonization policies for the Portuguese economy. The emissions constraint suggests that the tax on CO_2 emissions will need to increase from its current level of 5€/tCO_2 to 33€/tCO_2 in 2030, 49€/tCO_2 in 2040 and 183 €/tCO_2 in 2050.

By design, the different decarbonization policies based on carbon taxes, energy taxes and consumption taxes yield the same tax revenues for the public sector. Such revenues are used to reduce the public deficit. To have a sense of the **magnitude of these policies**, given the marginal cost implied by the TIMES_PT model, these pricing policies would generate revenues for the public sector equal to approximately 0.1% of 2015 GDP in 2020, 1% in 2030, 1.1% in 2040 and 2.5% in 2050.

To benchmark our results, we now focus on the most direct economic counterpart to the TIMES_PT decarbonization policies in defining the **marginal costs of emissions reductions as a tax on CO_2 emissions**.

A tax on CO_2 emissions would lead to **adverse effects on macro-economic performance** (Table 4) in terms of GDP (-4.3%), private consumption (-2.4%) and investment (-2.9%), as well as a deterioration of the trade balance and a 5.3% increase in foreign debt. The tax would similarly produce adverse labor market effects and reduce employment by 2.1% relative to the reference scenario in 2050. Naturally, and by design, the tax on carbon would contribute to significant **improvements in the public budgetary** situation, allowing for a 12.6% reduction in the public debt to GDP ratio in the long run. This is to be expected because the carbon tax revenues are allocated to general budgetary purposes by design.

A tax on CO_2 emissions would also lead to **adverse distributional effects (Table 5) and is thereby regressive in nature**. Indeed, the equivalent variation in income to the tax on carbon is substantially larger for lower income households than for wealthier households which raises social justify concerns. These larger welfare effects stem from labor supply responses, lower after-tax incomes and higher consumer prices which impose a substantially larger burden on lower-income households. Households in the lowest income quintile are expected to see a 3.3% reduction in welfare with the tax on carbon while the loss in income for those in the highest income quintile is substantially less – a 1.8% reduction in welfare.

The economic mechanisms underlying decarbonization strategies imply a somewhat less environmentally effective policy in reducing emissions (Table 3). The more limited substation possibilities coupled with more substantial demand responses suggest that behavioral responses may limit the overall effectiveness of policies to reduce emissions and suggest greater marginal costs of control. Total energy demand decreases by 14.4%, substantially more than the 5.7% reduction in the demand for electricity which suggests some substitution towards electricity and increase in electrification of the Portuguese economy. This translates to

Table 3 | Long Run [2050] Environmental effects (Percent Change Relative to the Reference Scenario)

	Energy Demand	Electricity Demand	Electricity Share	RES	CO2 Emissions
Carbon Tax	-14.4	-5.7	10.8	9.1	-24.3
Energy Tax	-7.6	-4.5	3.6	1.8	-9.4
VAT Tax	-3.9	-2.5	1.3	0.6	-4.8

Table 4 | Long Run [2050] Macroeconomic Effects (Percent Change Relative to the Reference Scenario)

	GDP	Consumption	Investment	Employment	Public Debt	Foreign Debt
Carbon Tax	-4.3	-2.4	-2.9	-2.1	-12.6	5.3
Energy Tax	-2.3	-1.1	-1.6	-1.1	-4.9	3.0
VAT Tax	-2.4	-0.7	-3.2	-1.3	-8.3	3.0

Table 5 | Long Run [2050] Distributional Effects (Percent Change Relative to the Reference Scenario)

Equivalent variation	Carbon Tax	Energy Tax	VAT Tax
First Quintile (Lowest Income)	-3.3	-1.7	-1.3
Second Quintile	-3.1	-1.4	-0.9
Third Quintile	-2.5	-1.2	-0.6
Fourth Quintile	-2.3	-1.1	-0.6
Fifth Quintile (Highest Income)	-1.8	-0.9	-0.5

an increase of 10.8% in the share of electricity in final energy demand. The higher costs for carbon increases energy system costs and reduces the resources available for expenditure on other goods, services and inputs to production. This lowers demand while simultaneously encouraging substitution towards lower carbon energy vectors and inputs. These scale and substitution effects provide the incentives and mechanisms for households and firms to respond to higher prices for carbon. This is reflected also in a relative shift in production towards labor and capital inputs and within the energy sector to fuels with a lower carbon content and to renewable energies. The production of electricity from renewable sources increases by 9.1%. Overall, the economic mechanisms behind the reductions in emissions suggest a greater reliance on output reductions due to more limited substitution possibilities for fossil fuels and for electrification.

Overall, the carbon tax alone can produce favorable budgetary outcomes but with serious and severe costs reflected in the adverse economic and distributional implications of the decarbonization policy.

Two alternative sources of revenue to finance deficit reduction of the same magnitude as the carbon tax were considered as simple decarbonization strategies: a broad tax on energy consumption and a tax on all products, an extension of the VAT. In both alternative cases, **the broader tax bases contribute towards smaller adverse macro-economic and distributional effects** although these continue to produce negative and regressive effects on economic performance. Both of these tax scenarios, but particularly the VAT, lead to a more severe pattern of regressivity.

These two alternative pricing policies lead to **dramatically lower reductions in CO_2 emissions**. Clearly, a carbon tax, being a much more focused instrument, is much more effective in curtailing emissions.

The adverse macro-economic and distributional effects of the tax on CO_2 emissions motivate the need to consider a more comprehensive environmental fiscal reform that has the potential to reduce emissions, promote economic growth and job creation and address public sector budgetary concerns.

Comprehensive environmental fiscal reform provides for a politically feasible mechanism to address environmental, economic, industry and social concerns associated with decarbonization policies and promote positive and progressive economic outcomes. Environmental fiscal reform is made possible through the proceeds generated by the tax on CO_2 emissions. These revenues can be used to finance reductions in the personal income tax (PIT), corporate income tax (CIT), value added taxes (VAT) and to finance investment tax credits (ITC) for private capital. These changes are considered in isolation and together with incentives for the purchase of **energy efficient equipment and technologies,** including selected reduction in the VAT and personal income tax credits for energy efficiency appliances as well as corporate income tax deductions and investment tax credits for the purchase of energy efficiency equipment and technologies.

We start by considering **policy options in which the revenues from the tax are used to reduce individual tax margins** with and without incentives for energy efficiency improvements. Progressive changes to the personal income taxes can always produce progressive distributional effects for the decarbonization policies. Generally, the use of carbon tax revenues to reduce the personal income tax rate and VAT rates are particularly effective in reducing the adverse distributional effects of the carbon tax. In turn, reductions to the corporate income tax and financing for private investment tax credits are particularly effective in reducing the adverse economic effects and can, in some instances, encourage economic growth and job creation.

The effects of the reducing taxes at the different margins suggests that multiple policy objectives may be achievable with a environmental fiscal reform based on **mixed recycling strategies**. We first consider a direct tax channel: a combination of reductions in the PIT and the CIT tax margins; we then consider an indirect tax channel, a combination of reductions in the VAT and increases in the ITC; finally, we consider a combination of reductions in the PIT and increases in the ITC. In all cases, we consider a detailed grid of alternatives for the share of CO_2 tax revenues allocated to reductions in each tax margin to determine the most desirable outcome with respect to economic performance and distributional considerations. In each case, we consider the use of part of the revenues generated to provide PIT and CIT credits, VAT rate reductions and increases in the ITC for the purchase of energy efficient technologies.

We conclude that a balanced **50/50 mixed direct channel strategy of personal income tax and corporate income tax** reductions, a balanced **50/50 mixed indirect channel of reductions to the value added tax and financing for investment tax credits** and a balanced **50/50 mixed of reductions to the personal income tax and financing for investment tax credits** can each yield all of the desirable policy outcomes: reductions in GHG emissions, positive macro-economic effects, progressive distributional effects, reductions to the public sector debt, and positive effects on international competitiveness.

First**,** environmental fiscal reform is **effective in reducing CO_2 emissions** (Table 6). Overall, these policies tend to be more effective when part of the reduction in the PIT and the VAT are specific to energy efficiency improvements. When these improvements are considered, all 50/50 mixed recycling strategies lead to a CO_2 reduction of 24-25% in 2050, i.e., similar to the carbon tax alone.

Second, environmental tax reform with mixed revenue recycling strategies can promote **positive economic outcomes** (Table 7): GDP gains and more substantial gains in employment. Reform can promote a significant improvement of the long term foreign debt position by encouraging exports. These policies also yield an **improvement in the long -term public debt** position for the public sector, despite the revenue neutral implementation, due to expanding tax bases in response to the positive economic outcomes.

Finally, environmental fiscal reform with mixed revenue recycling strategies has the potential to produce **positive and progressive distributional effects (Table 8)**. Environmental fiscal reform may significantly reduce the welfare losses associated with decarbonization policies and yield positive and progressive distributional effects. With appropriate adjustments to the personal income tax rates for lower income households, environmental fiscal reform can allow for positive welfare effects and address existing social justice concerns.

Environmental fiscal reform provides a politically and economically feasible mechanisms for realistically implementing the technologically feasible options identified with the TIMES CO_2-60% scenario. They lead to the desired environmental outcomes while at the same time encouraging positive and progressive economic outcomes, contributing towards public debt reduction and promoting the international competitiveness of the Portuguese economy.

TABLE 6 | LONG RUN [2030, 2050] ENVIRONMENTAL EFFECTS (PERCENT CHANGE RELATIVE TO THE REFERENCE SCENARIO)

	Energy Demand		Electricity Demand		Electricity Share		RES		CO2 Emissions	
	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
Carbon Tax	-3.6	-14.4	-1.2	-5.7	2.7	10.8	2.3	9.1	-5.0	-24.3
PIT – CIT (50/50)	-3.0	-12.8	0.6	-1.5	4.0	14.3	2.3	9.6	-5.3	-25.1
VAT – ITC (50/50)	-2.9	-12.7	0.2	-2.2	3.6	13.0	2.0	9.2	-5.1	-24.4
PIT – ITC (50/50)	-3.1	-13.1	0.3	-1.9	3.8	13.9	2.0	9.2	-5.3	-25.1

TABLE 7 | LONG RUN [2030, 2050] MACROECONOMIC EFFECTS (PERCENT CHANGE RELATIVE TO THE REFERENCE SCENARIO)

	GDP		Consumption		Investment		Employment		Public Debt		Foreign Debt	
	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
Carbon Tax	-1.0	-4.3	-0.4	-2.4	-0.4	-2.9	-0.5	-2.1	-1.4	-12.6	0.8	5.3
PIT – CIT (50/50)	0.8	0.1	0.3	0.1	2.5	2.8	0.6	0.5	-0.1	-8.2	-1.7	-8.5
VAT – ITC (50/50)	0.4	0.0	0.2	-0.7	2.0	6.2	0.4	0.6	0.2	-4.8	-1.5	-6.8
PIT – ITC (50/50)	0.5	0.2	0.2	-0.5	2.2	-0.5	0.5	0.9	0.5	-5.3	-1.4	-6.6

TABLE 8 | LONG RUN [2030, 2050] DISTRIBUTIONAL EFFECTS (PERCENT CHANGE RELATIVE TO THE REFERENCE SCENARIO)

Equivalent variation	Carbon Tax		PIT – CIT (50/50)		VAT – ITC (50/50)		PIT – ITC (50/50)	
	2030	2050	2030	2050	2030	2050	2030	2050
First Quintile (Lowest Income)	-0.7	-3.3	0.8	0.8	0.4	-0.4	0.7	0.5
Second Quintile	-0.6	-3.1	0.6	0.4	0.3	-0.7	0.5	-0.1
Third Quintile	-0.4	-2.5	0.3	0.1	0.2	-0.8	0.2	-0.5
Fourth Quintile	-0.4	-2.3	0.2	-0.0	0.2	-0.7	0.1	-0.6
Fifth Quintile (Highest Income)	-0.3	-1.8	0.1	-0.1	0.1	-0.6	0.0	-0.8

References

APA - Agência Portuguesa do Ambiente (2012). RNBC Roteiro Nacional de Baixo Carbono 2050 - Opções de Transição para uma Economia de Baixo Carbono Competitiva em 2050. Agência Portuguesa do Ambiente. Amadora. Lisboa, Portugal. Disponível em: https://www.apambiente.pt/_zdata/DESTAQUES/2012/RNBC_COMPLETO_2050_V04.pdf.

APA - Agência Portuguesa do Ambiente (2015). PNAC - Programa Nacional para as Alterações Climáticas 2020/2030. Agência Portuguesa do Ambiente. Amadora. Lisboa, Portugal. Disponível em: http://sniamb.apambiente.pt/infos/geoportaldocs/Consulta_Publica/DOCS_QEPIC/150515_PNAC_Consulta_Publica.pdf.

APA (2014). Portugal National Inventory Submission 2014. Portuguese Environment Agency

Berst, J (2008). The Electricity Economy - New Opportunities from the Transformation of the Electric Power Sector. August 2008, pp.55. Global Environment Fund and Global Smart Energy. USA.

EC - European Commission, COM(2014) 15 final. Communication from the Commission to the Council, the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A policy framework for climate and energy in the period from 2020-2030, European Commission, Brussels, 2014. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52014DC0015.

EC - European Commission, COM(2016) 860 Final Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee, the Committee of the Regions and the European Investment Bank - Clean Energy For All Europeans, Brussels, 2016. http://eur-lex.europa.eu/resource.html?uri=cellar:fa6ea15b-b7b0-11e6-9e3c01aa75ed71a1.0001.02/DOC_1&format=PDF.

EC (2011). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A roadmap for moving to a competitive low carbon economy in 2050 (COM(2011) 112 final). Brussels: European Commission.

EURELETRIC (2017). A Bright Future for Europe-The value of electricity in decarbonising the European Union. 47 pp. Brussels. Available at: http://www.eurelectric.org/media/318404/electrification_report_-_a_bright_future_for_europe-2017-030-0291-01-e.pdf.

Fortes, P, Pereira R, et al. (2014) Integrated technological-economic modeling platform for energy and climate policy analysis. Energy 73, 716–730.

Fortes, P., Alvarenga, A., Seixas, J. and Rodrigues, S. (2015). Long-term energy scenarios: Bridging the gap between socio-economic storylines and energy modeling, Technol. Forecast. Soc. Change, 91, 161–178.

Fortes, P., S. Simões, J. Seixas, D. Van Regemorter, F. Ferreira (2013). Top-down and bottom-up modelling to support low-carbon scenarios: climate policy implications, CLIMATE POLICY. 13, 285–304.

Fraunhofer ISE (2015a). Current and Future Cost of Photovoltaics. Fraunhofer Institute for Solar Energy Systems. Available at: https://www.agora-energiewende.de/fileadmin/Projekte/2014/Kosten-Photovoltaik-2050/AgoraEnergiewende_Current_and_Future_Cost_of_PV_Feb2015_web.pdf.

Fraunhofer ISE (2015b). Discount rates in energy system analysis. Buildings Performance Institute Europe. Available at: http://bpie.eu/uploads/lib/document/attachment/142/Discount_rates_in_energy_system-discussion_paper_2015_ISI_BPIE.pdf.

Gouveia, J.P.; Fortes, P.; Seixas, J. (2012). Projections of Energy Services Demand for Residential Buildings: Insights from a Bottom-up Methodology. Energy 47 (2012) 430-442.

IEA - International Energy Agency (2016), World Energy Outlook 2016, Paris.

OECD/IEA and IRENA (2017). Perspectives for the Energy Transition - Investment Needs for a Low-Carbon Energy System. 204 pp. Available at: http://www.irena.org/DocumentDownloads/Publications/Perspectives_for_the_Energy_Transition_2017.pdf.

Loulou, R., Remme, U., Kanudia, A., Lehtila, A., Goldstein, G. (2005a). Documentation for the TIMES model - PART I.

Loulou, R., U. Remme, A. Kanudia, A. Lehtila, G. Goldstein (2005b). Documentation for the TIMES model - PART II. www.etsap.org/tools.htm.

Pereira, A., and R. Pereira (2012). DGEP - A dynamic general equilibrium model of the Portuguese economy: model documentation. The College of William and Mary, Working Paper 127 (Revised 2014).

Pereira, A., and R. Pereira (2014a). Environmental Fiscal Reform and Fiscal Consolidation: The Quest for the Third Dividend in Portugal. Public Finance Review 42(2): 222-253.

Pereira, A., and R. Pereira (2014b). On the environmental, economic and budgetary impacts of fossil fuel prices: A dynamic general equilibrium analysis of the Portuguese case. Energy Economics 42(C): 248-261.

Pereira, A., and R. Pereira (2016a). Marginal Abatement Cost Curves and the Budgetary Impact of CO2 Taxation in Portugal, Environmental and Resource Economics, forthcoming, available online.

Pereira, A., and R. Pereira (2016b). On the Relative Roles of Fossil Fuel Prices, Energy Efficiency, and Carbon Taxation in Reducing Carbon Dioxide Emissions: The Case of Portugal. Journal of Environmental Planning and Management, forthcoming, available online.

Pereira, A., and P. Rodrigues (2002). On the Impact of a Tax Shock in Portugal. Portuguese Economic Journal 1(3):205-236.

Pereira, A., and P. Rodrigues (2004). Strategies for fiscal reform in the context of the EMU: the case of Portugal. Review of Development Economics 8(1): 143-165.

Pereira, A., and P. Rodrigues (2007). Social Security Reform in Portugal: A Dynamic General Equilibrium Analysis. Portuguese American Development Foundation, Lisbon.

PORDATA (2016). Europe – Environment, Energy and Territory. PORDATA. Available at: www.pordata.pt.

Seixas, J., P. Fortes, L. Dias, J.E. Barroso, S. Martinho, J.P. Gouveia, F. Ferreira, P. Gomes, H. Tente, P. Baptista (2014). Cenários de emissões de GEE e opções tecnológicas de descarbonização para Portugal em 2020 e 2030. Faculdade de Ciências e Tecnologia- Universidade Nova de Lisboa. Estudo Técnico de Suporte ao PNAC 2020. Agência Portuguesa do Ambiente, Lisboa.

Simoes, S., Fortes, P., Seixas, J., Huppes, G. (2015). Effects of exogenous assumptions in GHG emissions models - A 2020 scenario study for Portugal using the Times model. Technol. Forecast. Soc. Change, 94. pp. 221-235.

Simoes, S., J. Cleto, P. Fortes, J. Seixas, G. Huppes (2008). Cost of energy and environmental policy in Portuguese CO2 abatement-scenario analysis to 2020, Energy Policy. 36, 3598 –3611.

Simoes, S., Seixas, J., Fortes, P., Huppes, G. (2014). The Savings of Energy Saving: Interactions between energy supply and demand side policies - quantification for Portugal. Energy Efficiency Journal Vol. 7, Issue 2, pp. 179-201.

Seixas, J., Simões, S., Fortes, P., Dias, L., Gouveia, J., Alves, B., & Maurício, B. (2010). Novas Tecnologias Energéticas: RoadMap Portugal 2050 [New Energy Technologies: RoadMap Portugal 2050] (p. 88). Lisbon.

Seixas, J., Fortes, P., Dias, L., Dinis, R., Alves, B., Gouveia, J., Simões, S. (2012). Roteiro Nacional de Baixo Carbono: Portugal 2050 - Modelação de gases com efeito estufa, Energia e Resíduos [Low Carbon RoadMap: Portugal 2050 - Energy and Waste Greenhouse emissions]. Lisbon. Available at: http://www.apambiente.pt/_zdata/RNCB/EnergiaResiduos_10_07.pdf.

Williams, J.H., B. Haley, F. Kahrl, J. Moore, A.D. Jones, M.S. Torn, H. McJeon (2014). Pathways to deep decarbonization in the United States". The U.S. report of the Deep Decarbonization Pathways Project of the Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations.

Williams, H, DeBenedictis, A. et al (2012) The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity. Science 335 (53), 53-59.