Untangling the web : integrating energy and environmental policy instruments by assessing their interactions along power systems

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6 Top-down and bottom-up modelling to support low carbon scenarios: climate policy implications*

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Abstract

Bottom-up (BU) and top-down (TD) models have been supporting climate policies, identifying the options required to meet greenhouse gases (GHG) abatement targets and evaluating its economic impact. Some studies have shown that GHG mitigation options from economic TD and technology BU models tend to vary, being different baseline scenarios one recognised divergence factors. This article explores the use of TIMES_PT (BU) and the general equilibrium GEM-E3_PT (TD), assessing the extent of their differences in mitigation options when calibrated to a common baseline scenario and how different outcomes are relevant for domestic climate policy making. Three low carbon scenarios were generated until 2050, with different GHG reduction targets for the case study of Portugal.

The models present close mitigation options, allocating the larger mitigation potential to energy supply. However, they suggest different in mitigation options for end-use sectors. GEM-E3_PT focuses more on energy efficiency, while TIMES_PT relies on carbon intensity decrease by shifting to electricity. Common baseline scenario cannot be ignored but the models inherent characteristics' are the key factor for different outcomes, highlighting different mitigation recommendations.

6.1 Introduction

The need to limit the negative impacts of climate change has motivated several countries and regions to set greenhouse gases (GHG) emissions reduction pledges in the medium (UNFCCC, 2011) and long term (e.g. EC, 2011; HMG, 2008; MFE, 2011). Many studies have been conducted to design decarbonization scenarios (see Hughes and Strachan, 2011 and Söderholm et al., 2011 for a review on low carbon scenarios). Energy-economic-environmental models are extensively used to outline how the transition to a low carbon economy can be achieved and to evaluate its economic impacts.

E.g. macro-economic top-down and technological bottom-up frameworks are the two main modelling approaches, differing in the emphasis placed on energy technologies and the comprehensiveness of endogenous market adjustments (Böhringer and Rutherford, 2008). Conventional bottom-up (BU) models follow a partial equilibrium representation of the energy system, describing it with high technological detail. They solve optimization problems, computing the least-cost combination of energy technologies to meet energy services demand. BU models often ignore the macro-economic feedbacks of different energy system pathways or consider them partially through energy services demand adjustments, dependent on their endogenous energy costs and exogenous price-elasticities. Although some studies evidence that price elasticities capture a relevant part of the feedback effects from economy to energy system (Bataille, 2005; Labriet et al., 2010), BU models do not include the full macro-economic feedback, being unable to assess all the economic impacts of climate and energy policies such as on GDP, production, labour.

Conventional top-down (TD) models, namely Computable General Equilibrium (CGE) models, describe the interaction between the energy system and the economy as a whole, following the Arrow-Debreu economic equilibrium paradigm. They represent the energy sector in an aggregated form by production functions, capturing substitution possibilities through elasticities of substitution (Böhringer, 1998) and setting energy savings through an autonomous energy efficiency index (AEEI). These are usually estimated from aggregated historical data, with no guarantee that they will remain valid in the future (Grubb et al., 2002). Therefore, CGE models suggest that efforts to change the energy system away from a specific form, namely as response to GHG abatement, tend to be costly (Grubb et al., 1993; Hourcade et al. 2006; IPCC, 2001; Rivers and Jaccard, 2005; Wilson and Swisher, 1993).

Some efforts to integrate the two modelling paradigms in hybrid models (Hourcade et al., 2006) have been made, assuming a soft-link between two independent TD and BU models, complement one model to a reduce form of the other, introduce discrete technologies (mostly electricity generation) in CGE models through a mixed complementary problem, or integrate the two models through a decomposition algorithm which employs an iterative procedure (see Labriet, 2010 and Lanz and Rausch, 2011 for a detailed overview). The primary difficulty arising from most of these methods lies in the inherent computational challenges, being assumed simplified forms of the models which do not allow capturing the global strengths of both approaches. Thus, conventional use of CGE and BU models continues to support extensively climate policy studies.

Some earlier studies have confronted the results of both approaches under carbon mitigation targets, comparing abatement costs (Grubb et al., 1993; IPCC, 2001; Wilson and Swisher, 1993). More recent analysis, as from Intergovernmental Panel on Climate Change (2007) and Van Vuuren et al. (2009) assessed also the sectoral reduction potential from both approaches, finding considerable differences in the level of sector abatement from BU and TD models, with TD indicating higher reductions for energy supply and industry. However, the studied models used different baseline scenarios and, in some cases, even different assumptions. Dissimilar baseline scenarios can limit the results' comparison, since In climate mitigation modelling besides the structural characteristics of the models and the climate policy regime considered, base case emissions represent one of the factors that can drive model outcomes (Fischer and Morgenstern, 2006). Most of multi-models comparison studies (e.g. ACROPOLIS (Das et al., 2007) and ADAM (Edenhofer, et al., 2010) projects and the Energy Modeling Forum (Clarke et al., 2009)) do not consider however common baseline emissions, focus primarily on analysing the modelling tools and results. Harmonised baseline scenarios include energy consumption and emissions, plus other exogenous assumptions (e.g. GDP, population, energy import prices). By setting a common baseline, it is possible to conclude that different TD and BU outcomes, under similar climate policy regime, are a result only of the models structure and characteristics (e.g. energy substitution elasticities, technology data).

This article aims to explore the relevance of the modelling approach used to support climate policy mitigation, by: (1) identifying to what extend the BU TIMES and the CGE GEM-E3 models, applied for the case study of Portugal and considering a common baseline, lead to different abatement strategies and (2) how possible dissimilar outcomes could result in different domestic climate policy recommendations. To achieve these objectives we compare the models strategies to reduce sector emission using modified Kaya identity.

The paper is organized as follows: Section 6.2 summarizes the modelling framework, the baseline calibration process and outlines the low carbon scenarios. Section 6.3 presents models results, comparing the GHG reductions per sector, carbon mitigation strategies and marginal abatement costs. Section 6.4 discusses the impact on domestic climate policy and Section 6.5 concludes.

6.2 Modelling Framework

The BU TIMES_PT and the CGE GEM-E3_PT were used to generate the baseline and three low carbon scenarios for Portugal up to 2050. TIMES and GEM-E3 models have been broadly used to assess the impact of European Union (EU) or EU countries climate policies (Blesl, 2012; Criqui et al., 2003; EC, 2008; Proost et al., 2009; Russ et al., 2009), but mitigation options from these models have never been compared. In this paper, to ensure that possible divergences between models' results are not due to different reference state and assumptions, the models were initially calibrated to a common baseline scenario. This section, presents a brief characterization of the two models, as well as, the calibration process for setting a similar baseline scenario and the low carbon scenarios developed.

6.2.1 GEM-E3_PT Model

GEM-E3 (General Equilibrium Model for Economy, Energy, Environment) is a multi-region, multi-sector, recursive dynamic computable general equilibrium model (E3M Lab, 2010). Adopting the quantitative application of the Arrow-Debreu economic paradigm, GEM-E3 computes the equilibrium prices of goods, services, labour and capital that simultaneously clear all markets and optimize the behaviour of economic agents. Its production technology is represented by constant substitution elasticity (CES) production function. The CES function combines primary factors with intermediate consumption of materials, services and energy in a four-level nested structure.

GHG emissions abatement by the production sectors results from three strategies available: i) fuel switch to low carbon options (i.e. decrease of carbon intensity), driven by substitution elasticities between energy carriers: electricity, oil, natural gas and coal (E3M Lab, 2010); ii) increase of energy efficiency (i.e. decrease energy intensity), by substituting energy for other production factors, i.e. materials, labour or capital (this can also translate a shift to renewables, which cannot be differentiated in this model), and iii) reduction of activity levels (i.e. reduction of domestic production). On the consumer side, the mitigation options are mainly driven by energy saving through the energy demand price elasticities.

GEM-E3_PT corresponds to a single country version of GEM-E3 for Portugal, assuming eighteen productive sectors (Appendix A). The 2005 benchmark Social Accounting Matrix was built from Use and Supply IO tables, published by Eurostat (Eurostat, 2009) and for the transfers between sectors from the Portuguese National Accounts of the National Statistics Institute (INE, 2008). The calibration of the energy consumption was made by crossing the national energy balances (DGGE, 2007) with the energy prices published by the International Energy Agency (IEA, 2008). Through the use of aggregated CO_2, CH_4 and N_2O emissions factors for coal, oil and natural gas, supported by the 2005 energy balance, the GHG generated by each productive sector and category of consumption were computed and calibrated with the national GHG inventories (APA, 2012).GEM-E3_PT CES nesting structure differs from the standard GEM-E3 (E3M LAB, 2010) in the second level where the composite factor labour, energy, and materials (LEM) is split by the three components. At the third level CES functions defines the substitution between materials types, as defines (separately) energy substitution between electricity and a fossil fuel aggregate (coal, oil and natural), which is divided at the succeeding level. The substitution possibilities are set through constant elasticities derived from international econometric studies and literature review as explain in detail in E3M LAB (2010). CES varies between 0.4 and 0.5 up to LEM factors, being the range of elasticities values between the energy sources higher (0.5 between fossil fuels aggregate and electricity and from 0.4 to 0.9 between fossil types for transports and energy intensive industries, respectively). TIMES_PT model

TIMES (The Integrated MARKAL-EFOM system) is a dynamic linear optimization model generator, which simulates regional or multiregional energy systems (Loulou et al., 2005). Based on a technology database and external constraints (e.g. GHG emissions caps, fossil fuels import prices and energy sources potential), TIMES computes the energy supply/demand equilibrium, where both supply and demand are adjusted to changes in prices under perfect foresight. The ultimate goal of TIMES is to satisfy energy services demand at the minimum system cost, making simultaneous decisions about equipment investment and operation, primary energy supply and energy trade (Loulou et al., 2005).

TIMES-PT maps the Portuguese energy system, modelling in detail energy supply (petroleum refining) and power sector, as well as final energy consumption sectors, namely, industry, residential, commercial, agriculture and transport, which are disaggregated in several subsectors (Appendix A).

The technology database in the model includes the characteristics of the existing and future energy technologies, as efficiency, capacity factor, availability, technical lifetime, investment, operation and maintenance costs. The data has been updated within European Projects and international bibliography, and validated by national stakeholders. TIMES_PT is calibrated to 2005 national energy balances (DGEG, 2007) and includes CO_2, CH_4 and N_2O combustion and process emissions, which are calculated and calibrated through emissions factors per energy carrier and/or sector from the national GHG inventories (APA, 2012). Like GEM-E3_PT, TIMES_PT assumes the same strategies to reduce GHG abatement: i) carbon intensity decrease, by choosing technologies that provide the same service with a less carbon intensive fuel (i.e. substitution of a boiler on coal with a boiler on gas); ii) energy intensity reduction through more efficient technologies; and iii) the reduction of activity levels (i.e. reduction of energy services demand or mobility) via exogenous demand-price elasticities. TIMES_PT assumes a price elasticity of -0.3 for almost all demands categories, supplied by Katholieke Universiteit Leuven, and assumed as a generic value valid for the EU countries. Although TIMES can also reduce GHG emission through carbon capture and storage technologies, this mechanism was not considered as explained in the next section.

6.2.2 Calibration methodology for a common baseline scenario

GEM-E3 and TIMES have been applied together in several European projects, (e.g. NEEDS, RES2020, REALISEGRID), following a specific sequence: GEM-E3 computes demand drivers, such as GDP and sector domestic production growth that are used to determine energy services and materials demand evolution, used as TIMES inputs (see Step I of the calibration process). No further feedback of any kind has been considered.

To guarantee that both models are benchmark to a common Baseline scenario, without considering any climate mitigation target, we developed a calibration process based on a soft-link between the two models. The link follows an approach close to de one used by Labriet et al. (2010), exchanging prices and quantity variables (e.g. energy, emissions) between the models and solving them iteratively until reaching similar results (less than 10% difference). The overall calibration framework is presented in Figure 6.1 and explained in detail in this section.

The main assumptions of the Baseline Scenario in both models include: (i) annual real interest rate of 4%; (ii) fossil fuel import prices up to 2035 adopted from Current Policies Scenario of World Energy Outlook 2010 (IEA, 2010) and extended till 2050, namely \$162.0/barrel for crude oil, \$176.9/BTU for natural gas and \$124.5/ton for coal in 2050 (in year-2009 dollars); (iii) socio-economic scenario assuming an annual average GDP and population growth of 2.3% and 0.3%, respectively, between 2010 and 2050 (Seixas et al., 2010); (iv) technological assumptions: nuclear electricity generation ban and unavailability of carbon capture and storage technologies for the analysed time period, justified by the absence of this option in GEM-E3_PT.

The calibration process between the two models, as represented in Figure 6.1, followed the three steps described below.

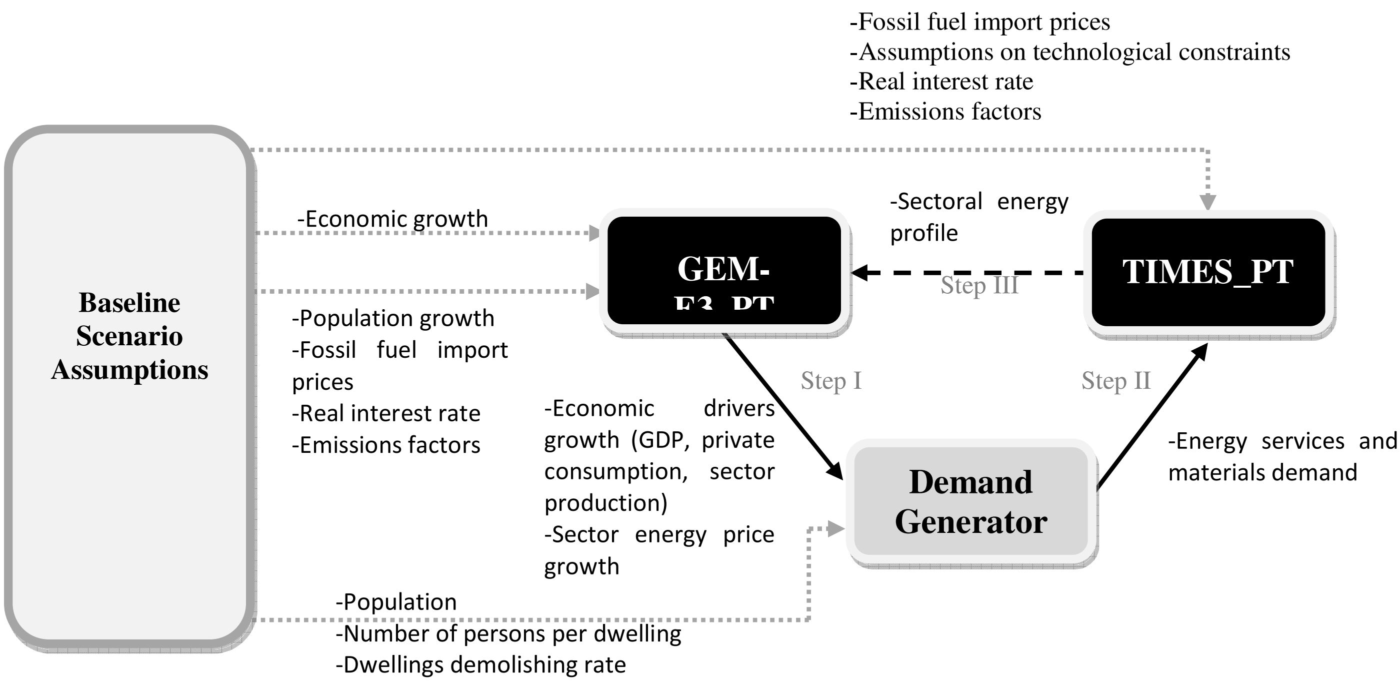


Figure 6.1 – GEM-E3_PT and TIMES_PT calibration framework. The dotted grey lines represent Baseline scenario assumptions (e.g. economic and population growth, fossil fuel import prices) or calibration parameters (e.g. real interest rate, emission factor); the black lines represent the iteration process: full black lines are direct inputs/outputs and the black dashed lines represent indirect inputs.

Step I: The economic drivers and total energy prices by sector generated by GEM-E3_PT through the optimization behaviour of the economic agents were used to produce energy services and materials demand evolution according to the equation of the demand generator from Van Regemorter and Kanudia, (2006) in Simões et al. (2008). The computation assumes a relation between the economic drivers and the total energy price growth with the evolution of energy services demand, given and autonomous efficiency improvement in industry.

Step II: The energy service and materials demand generated in step I are inputted into TIMES_PT, and the model is run to compute the least cost technological profile of the energy system, as energy consumption (quantities per sector per energy source) and corresponding GHG emissions.

Step III: The sectoral energy profile from TIMES_PT (both final and primary energy) for the time horizon is included in GEM-E3_PT where the energy efficiency evolution is associated with an exogenous AEEI. In most uses of GEM-E3 this variable is a fixed value derived from the literature and identical for all energy carriers and for all end-use energy sectors. In GEM-E3_PT, to ensure consistency between the two models, the parameter was disaggregated per energy carrier and per sector and adjusted according to TIMES_PT technological choices. Appendix A presents the eleven sectors considered in the calibration process and its correspondence with the models categories.. The goal of step III is to align in Baseline the models energy consumption and GHG emissions per sector..

Since modifications in sector energy consumption can induce changes on domestic production and consequently on energy services and materials demand, these three steps were repeated until each of the eleven sector's energy consumption per energy carriers from TIMES_PT and GEM-E3_PT converged, i.e. achieved a minor difference between them and relative to the previous iterative process (less than 10% or 1 PJ).

6.2.3 Low Carbon Scenarios

Three low carbon scenarios, differing from Baseline only in the level of GHG emission cap up to 2050 were imposed in GEM-E3_PT and TIMES_PT: +27% above 1990 energy-related emissions **(+27S)** (corresponds to maintaining the Portuguese commitment to Kyoto Protocol until 2050); -20% **(-20S)** and -60% **(-60S)**, with a constant annual decrease rate from 2015 onwards (Figure 6.2). From 2010 to 2015 the three scenarios assume the Portuguese commitment under the Kyoto Protocol: an increase of 27% of 1990 emissions. The total GHG caps consider only energy combustion emissions, corresponding to around 97% of the total energy GHG emissions in 2010 (APA, 2012) and no trade among sectors was modelled.

6.3 Results

This section presents the results of the Baseline (BS) scenario, and compares the mitigation options adopted by TIMES-PT and GEM-E3_PT for the low carbon scenarios, regarding the allocation of total GHG abatement effort across economic sectors, the strategies to achieve it, and the marginal abatement costs.

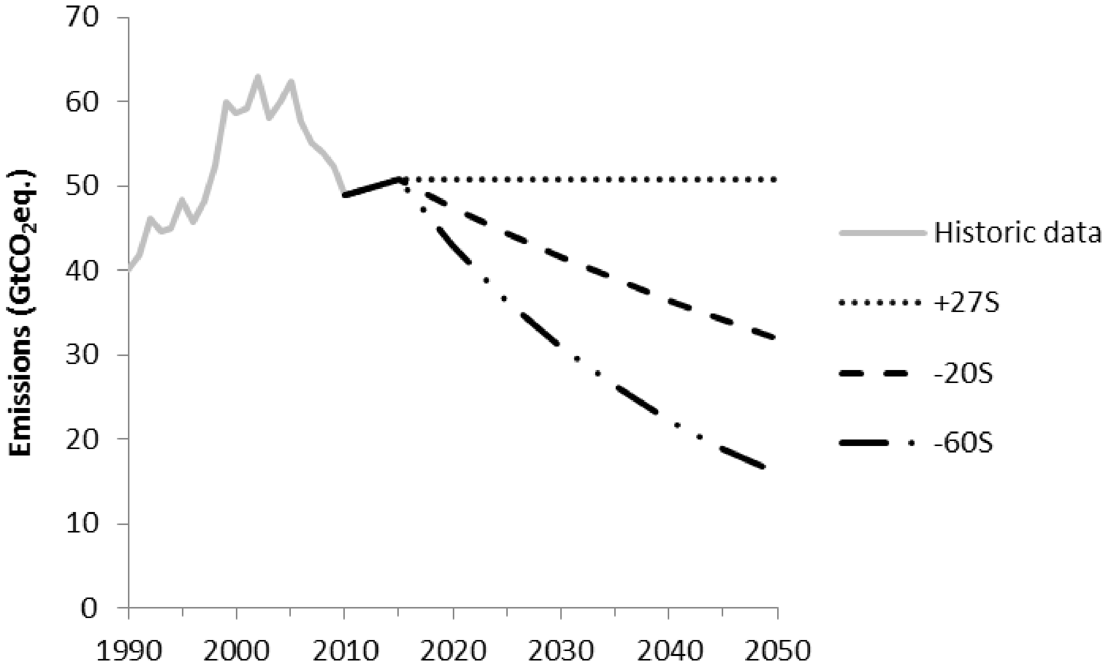


Figure 6.2 – Low carbon scenarios (+27S, -20S, -60S) (Note: High variability of historical GHG emissions data refers to the variability of hydrologic year. The modelling results relies on an average hydrologic year)

6.3.1 Baseline scenario

The models achieve high convergence in BS results regarding the consumption of energy and GHG emissions, with differences below 10% as set in the calibration process (Table 6.1). From 2005 to 2050, the final energy consumption in BS will increase more than 20%. Industry (ferrous and non-ferrous metals, chemical, energy intensive and other industries) has the biggest increase (27% for GEM-E3_PT and 29% to TIMES_PT), and buildings (services and residential) the smallest (13% to 18%). In BS without a GHG cap, power sector will rely on coal, increasing its relative share from 46% in 2005 to around 82% in 2050, since this is the cheapest technology/fuel. The consumption of renewable energy was not included in this estimate since it is not an explicit output of GEM-E3_PT, as mentioned in section 6.2.1. For both models, the energy supply (power sector and refinery) is the leading emitter followed by transport and industry. The main

GHG emissions reduction from 2005-2050 occurs in buildings (-14%) while transports are responsible for the main increase (22 to 27% for GEM-E3_PT to TIMES_PT, respectively).

6.3.2 Low Carbon Scenarios

6.3.2.1 GHG emissions reduction per sector

For the sake of simplicity, the following results are assessed by comparing with BS. The two models indicate that energy supply has the highest GHG abatement potential, as shown in Figure 6.3. Compared to BS, GEM-E3 reduces GHG emissions from 24% (in 2020 for +27S) to 90% (in 2050 for -60S), while TIMES_PT reduces from 35% to 82% for the same years and scenarios. In both models energy supply has the highest contribution for total abatement, but as the cap's stringency increases over time and scenario, its relative importance on total abatement decreases, as higher abatement is required from all other sectors. For the -60S in 2050, TIMES_PT allocates the biggest abatement to transport (43% of total abatement) due to a shift to biofuels and electricity based technologies. GEM-E3_PT presents lower substitution possibilities for this sector. In fact for private cars is not possible to substitute oil with electricity or natural gas, explaining the lower abatement level.

Industry has the second highest abatement potential (in percentage of reduction) in both models, except for -60S and -20S in 2050, when TIMES_PT places industry after transports and energy supply as these two sectors have considerable renewable and electricity technologies available, respectively.

In TIMES_PT, buildings have one of the least cost-efficient reduction options, with an abatement effort below 55% for -60S in 2050, while in GEM-E3_PT the reduction reaches 65%

Table 6.1 – Modelling results for Baseline scenario from GEM-E3_PT and TIMES_PT following the calibration process (renewable energy consumption not included)

	2005		**2020**		**2030**		**2050**		**Difference between the models (%)**			
	GEM-E3	TIMES	GEM-E3	TIMES	GEM-E3	TIMES	GEM-E3	TIMES	'05	'20	'30	'50
Final Energy consumption (PJ)	654	665	665	684	700	699	802	813	2	3	0	1
Agriculture	16	16	17	18	18	18	20	19	0	3	-1	-8
Industry	191	191	202	199	202	210	243	245	0	-2	4	1
Buildings	184	189	167	170	165	170	217	214	3	2	3	-1
Transport	264	269	278	297	314	301	322	335	2	7	-4	4
Energy consumption in power sector (PJ)	294	299	232	234	229	225	241	235	1	1	-2	-3
Coal	136	138	164	166	169	170	196	192	2	2	1	-2
Oil	69	70	5	5	0	0	0	0	2	-6	0	0
Natural Gas	90	90	63	63	60	55	45	43	1	0	-9	-5
GHG emissions (Gg CO2eq)	62923	63562	57484	59801	60009	60548	65467	67870	1	4	1	4
Agriculture	950	951	1048	1080	1096	1085	1093	1114	0	3	-1	2
Industry	9193	9311	9041	9008	9211	9590	11113	11251	1	0	4	1
Energy Supply	27025	27087	22046	22971	22238	23232	23995	24765	0	4	4	3
Transport	19820	20021	20841	22067	23598	22455	24159	25428	1	6	-5	5
Buildings	5936	6192	4509	4676	3867	4187	5107	5312	4	4	8	4

In general, in the long term GEM-E3_PT systematically shows higher emissions reductions than TIMES_PT for agriculture, industry and buildings. For energy supply and transports it is not as easy to highlight major trends between models as results vary across scenario, but mostly TIMES_PT results in higher reductions for energy supply than GEM-E3_PT. The differences in the models' sector abatement allocation are associated with their abatement possibilities represented by the technological database in TIMES_PT and by the CES function in GEM-E3_PT. Moreover, TIMES_PT results are based on an optimistic perspective about the future, where current immature technologies will become marketable in the long term. The model assumes that economic agents have perfect knowledge about the future and their choices are strictly rational. Thus, their investment decisions are not postponed by uncertain long term climate policies, by resistance to change due to imperfect information, or by subjective preferences. In opposition GEM-E3_PT has an imperfect knowledge of the future and its technological decisions are driven by exogenous substitution elasticities, based on historical data that integrate the above mentioned aspects.

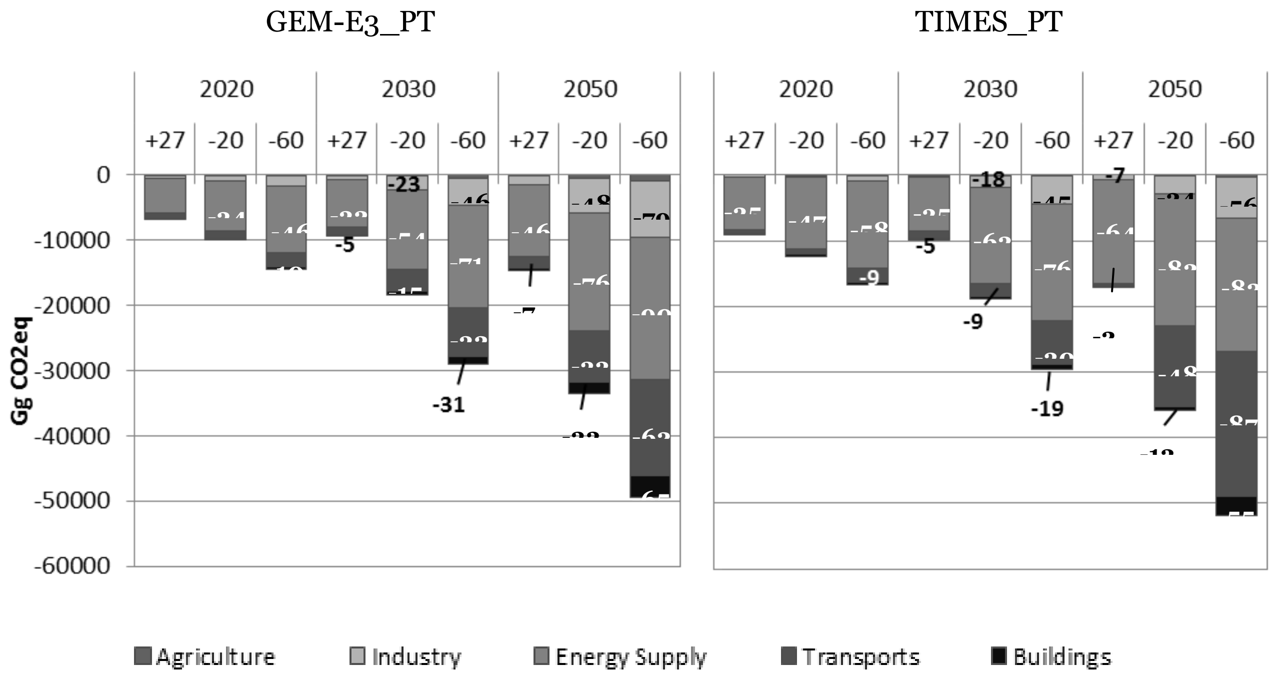


Figure 6.3– GHG emissions reduction (Gg CO2 eq. and percentage inside the bars) for the low carbon scenarios comparing to Baseline scenario (slightly differences in the total GHG emissions abated from the models are a result of the small divergences identify in Baseline).

To illustrate the policy significance of differences between model results regarding GHG reduction, we present the abatement effort using the EU climate and energy package metrics, i.e. comparing 2020 results with 2005 emissions included in the European Union GHG Emission Trading System (EU-ETS), and the energy component of the effort-sharing decision (non EU-ETS) (Table 6.2).

For simplification, it is assumed that the whole energy supply and energy intensive industry sectors are included in EU-ETS. Non EU-ETS includes emissions from agriculture, commercial, residential, transport sectors (including domestic aviation) and non-energy intensive industry.

For all scenarios TIMES_PT achieves a reduction effort for EU-ETS higher than GEM-E3_PT (five to seven percentage points), while the CGE model defines a higher abatement for non EU-ETS emissions (three to five percentage points) comparing to the BU model.

Both models suggest that decarbonization is foremost in EU-ETS sectors, as energy supply and energy intensive industry have the cheapest abatement options. Although there is no national target for EU-ETS emissions, both models found cost-effective to achieve a reduction above the EU target of 21% (EC, 2009a) even in +27S. However, in this scenario only for TIMES_PT is cost-efficient to achieve a -34% reduction target within the conditional increase of EU's total GHG emissions reduction from 20% to 30% in 2020 (EC, 2010).

Table 6.2 - Percentage of GHG emissions reduction in 2020 compared to 2005 disaggregated in EU ETS and non EU-ETS for the Low Carbon scenarios.

Scenario	Sector	GEM-E3_PT	TIMES_PT
+27% Scen.	EU-ETS	-32	-37
	Non EU-ETS	-6	-3
-20% Scen.	EU-ETS	-41	-48
	Non EU-ETS	-8	-3
-60% Scen.	EU-ETS	-50	-57
	Non EU-ETS	-12	-8

Under the EU Effort Sharing Decision, Portugal has a national target of 1% increase in 2020 from 2005 values (EC, 2009b). Still, the EU working paper about the analysis of options beyond 20% GHG emission reductions (EC, 2012) indicates that the Portuguese non EU-ETS emissions have a higher reduction potential, between 11 to 19%. Results show that the 11% reduction is only reached by GEM-E3_PT in -60S. This is relevant for policy-making and negotiations and demonstrates how important it is to understand the range of modelling tools used.

6.3.2.2 Abatement strategy

The Kaya Identity (Kaya, 1990) is widely used to assess the main drivers responsible for GHG emissions or for its abatement. By comparing the evolution of the factors of a modified Kaya identity (eq. 1) for each low carbon scenario with BS, it is possible to understand the strategy used by the two models to reduce GHG emissions. The original Kaya identity is associated to the whole economy, defining activity in terms of GDP and population. In this modified Kaya identity, the activity is associated with the respective sector, which can generally be expressed in domestic production for GEM-E3_PT or energy service demand for TIMES_PT. Although for end-use sectors it is not possible to establish a direct comparison between the models activity reduction (and consequently energy efficiency), as they assume different activity indicators, the factors evolution allows understanding the models abatement strategy for each sector. The three Kaya factors correspond to three main strategies for reducing GHG emissions mentioned in the models characterization (sections 6.2.1. and 6.2.2): reducing activity, energy intensity, and carbon intensity.

$$CO2\ emissions_s = activity_s{}^* \cdot \frac{Energy\ Consumption_s}{activity_s *} \cdot \frac{CO2\ emissions_s}{Energy\ consumption_s} \qquad \text{(eq. 1)}$$

$$\forall s = buildings, industry, transport, power\ sector \ldots$$

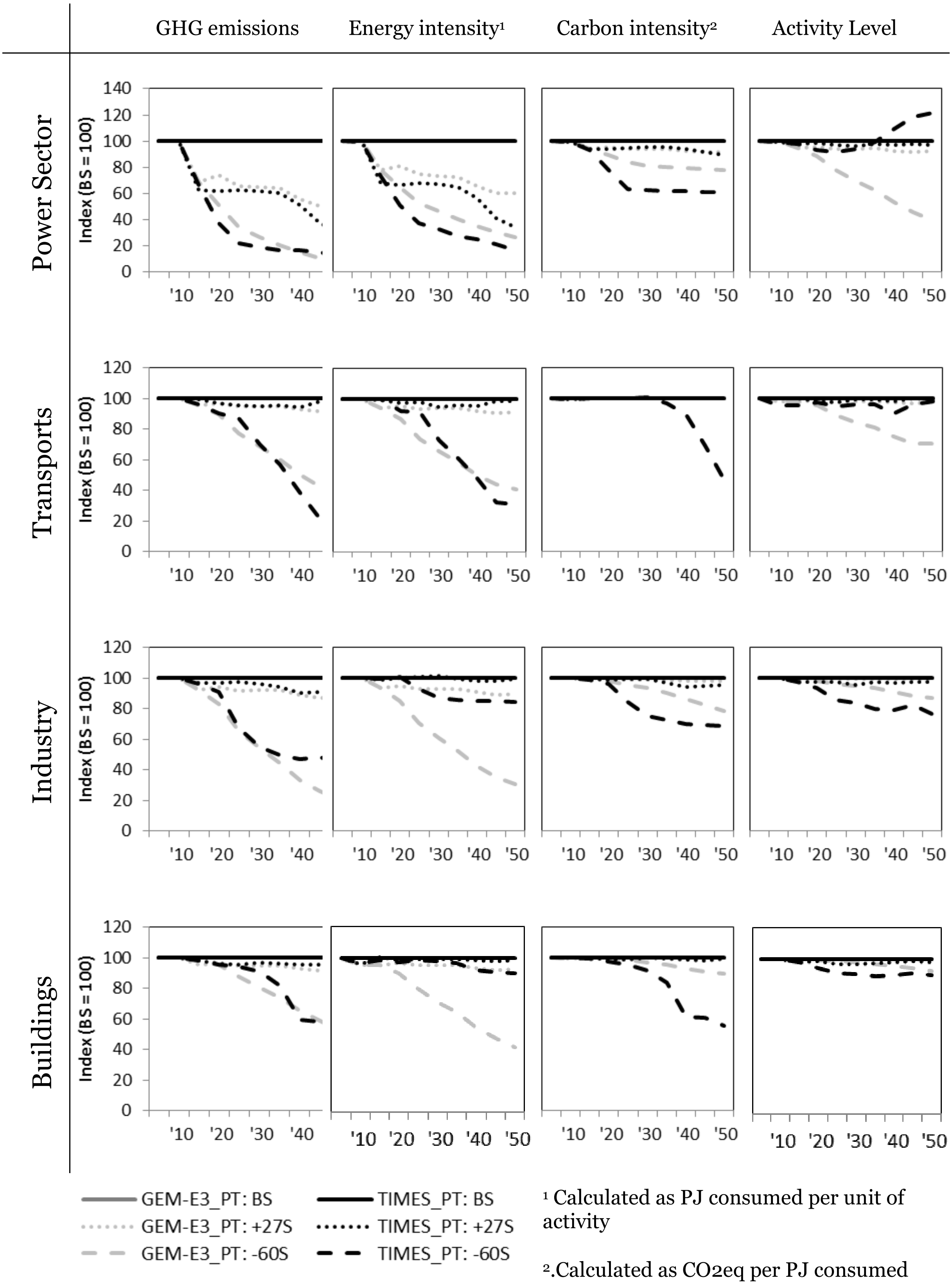
* In GEM-E3_PT activity refers to: sector domestic production in volume (M€'05) for industry, services, agriculture and transport services (i.e. freight and public transport), as well as private consumption (except fuels and power demand) (M€'05) for the residential and private transport sectors. In TIMES activity refers to: sector energy service demand (PJ) for buildings (residential and services) and agriculture, mobility (pkm, tkm) for

transport and materials and energy demand (ton and PJ) for industry. For both models the power sector activity corresponds to electricity production (PJ).

Figure 6.4 illustrates GHG pathways by sector and the respective Kaya drivers' evolution comparing with BS. For simplification the intermediate -20S and agriculture sector are not shown. In power sector, both models have a close emissions path and energy and carbon intensity reduction range. TIMES_PT shifts from coal to renewables decreasing fuel carbon intensity from around 10% to 39% (+27S to -60S) in 2050 compared to BS. GEM-E3_PT moves from energy consumption to other production factors (labour, materials and capital), representing investment in renewable energy, as well as more efficient equipment, decreasing the carbon intensity from 8% to 29% for the same year and scenarios. Although GEM-E3_PT reduces significantly the consumption of coal (37% to 66% compared to BS) it keeps using it, causing a lower carbon intensity reduction than TIMES_PT. In the more stringent target, and contrary to the CGE model, TIMES_PT increases the electricity production so the end use sectors can reduce its carbon emissions.

In general, GEM-E3_PT strategy to reduce end-use sectors is associated with a reduction of energy intensity, while TIMES_PT decreases mostly the carbon intensity and sector activity. GEM-E3_PT reduces more the total final energy than the share of fossil fuels (Figure 6.5). In 2050, for -60S, the final energy is reduced around 65% compared to BS, while the share of fossil fuel use just reduces 4 percentage points (from 73% in BS to 68%). On the contrary, TIMES_PT reduces more significantly the consumption of fossil fuels, less 34 percentage points (from 73% in BS to 39% in -60S in 2050), replacing them by electricity, and decrease less the final energy consumption (46% decrease in 2050 for -60S compared to BS).

Due to its technological database TIMES_PT has considerable options to reduce power sector emissions (supported by renewable technologies) and to substitute fossil energy consumption by electricity in end-use sectors. The CGE model focus more on demand side measures, as pointed by Van Vuuren et al., (2009), increasing the energy efficiency of end-use sectors through the substitution of energy for other production factors in the CES nest. Although electricity consumption is reduced in industry and buildings, its share in the sectors energy consumption increases, which can be associated to a shift from fossil to more efficient electric technologies.



[1] Calculated as PJ consumed per unit of activity

[2].Calculated as CO2eq per PJ consumed

Figure 6.4 - Comparison between GHG emissions, energy intensity, carbon intensity and activity level across models and scenarios (Baseline scenario (BS) = 100 over time) (excluding renewable energy).

In -60S, when a higher effort is necessary from end-use sectors, transport becomes the exception of these clearly different strategies. Besides carbon intensity TIMES_PT also reduces significantly its energy intensity, deploying high efficient electricity and hybrid plug-in vehicles. In GEM-E3_PT, the reduction of transports energy intensity is also accompanied by a reduction of its activity, decreasing -30% in 2050 in -60S. For the CGE model, transport is the end use sector that reduces less its energy consumption, maintaining always a high share of oil demand, regardless the scenario or year, which is reflected in its constant carbon intensity and represents a limitations of its substitution possibilities. .

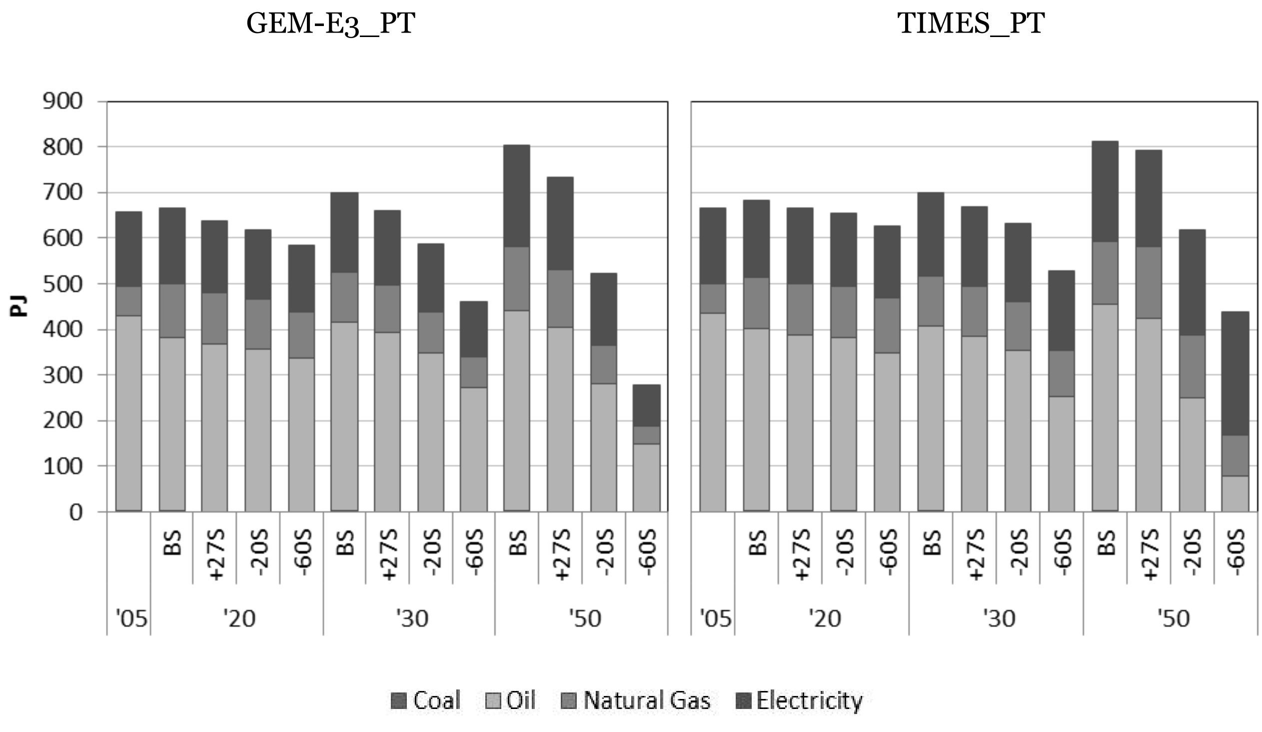


Figure 6.5– Final energy consumption by fuel (2005, 2020, 2030 and 2050) under Baseline and Climate Policy scenarios (Renewable energy not included)

6.3.2.3 Marginal Abatement Cost

The GHG emission reduction potential and abatement strategy defined by each model has a direct impact on abatement costs. Marginal abatement cost

(MAC) curves have been extensively used to assess the cost of a certain carbon abatement strategy, representing the shadow price of mitigation in a certain period. As mentioned by Kesicki and Ekins, (2010), the MAC curves are also in the focus of the climate policy debate, influencing decision making, namely by ranking abatement policies.

To plot the MAC curve for 2050 from both models results (Figure 6.6), additional GHG caps were run, representing a linear GHG emissions pathway from 2015 to 2050 until achieving in 2050: 0% (OS), -40% (-40S) and -50% (-50S) of GHG emissions vis-à-vis 1990 levels. All other assumptions of the three original low carbon scenarios and BS were maintained.

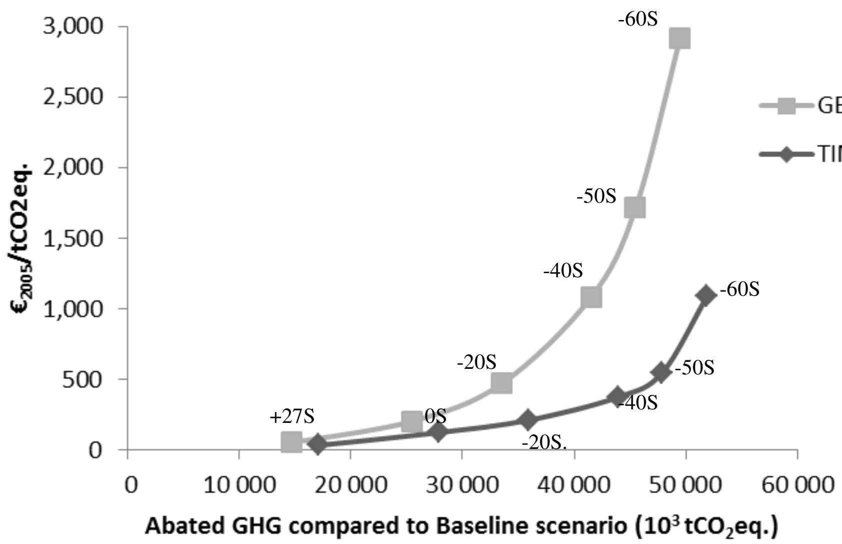


Figure 6.6 – Marginal abatement cost curve for the year 2050

As already observed by some authors (e.g. Jaccard et al., 2003; Hourcade et al., 2006, IPCC, 2001; Rivers and Jaccard, 2005), for the same level of reduction, the MAC from the CGE model is higher than from the BU models. The increase of the carbon reduction target from +27% to -60% denotes a corresponding increase of the carbon price from 54 to 2915€'05/t CO2eq from GEM-E3_PT, and only from 34 to 1075 €'05/t CO2eq from TIMES_PT. For higher GHG abatement levels, the relative difference between the MACs is higher, justified by different reduction strategies and sector potential. Historical substitution elasticities (as in GEM-E3_PT) make the economy's willingness to change the energy system away from GHG intensive technologies lower, (Jaccard et al., 2003) resulting in higher abatement costs. On the contrary, in BU models when technology costs are converted into present value through a social discount rate (e.g. 4% used), many technologies providing the same energy service and reducing GHG emissions appear to be profitable (Bataille et al., 2006), as the widespread use of electric and hybrid plug-in vehicles observed in TIMES_PT for -60S. The greater financial risk of new technologies, the fact that they may not be perfect substitutes to consumers and the availability of capital are usually not considered, resulting in lower mitigation costs from BU models. Moreover, TIMES_PT does not include the fully economic feedback represented in GEM-E3_PT (e.g. impact of the change in economic activity due to the GHG policies).

6.4 Discussion on policy considerations

BU and TD models are two of the most common tools used to support climate policy design, giving indications on the strategy required to meet GHG emissions caps. However, they are mostly used independently and without assuming harmonized baselines. Previous runs, without considering a common baseline scenario and without any cap were made. They present significant differences between the models outcomes (GEM-E3_PT GHG emissions were 13% to 48% higher than in TIMES_PT for 2020 and 2050, respectively). Thus, the abatement effort computed by each model to accomplish the GHG emission caps will be different. For -60S, and assuming the abatement effort comparing to base year, the results with and without common baseline have also shown relevant differences, especially for GEM-E3_PT buildings, agriculture and industry sectors. For industry for example, the difference in the abatement effort from non-harmonized GEM-E3_PT and TIMES_PT are higher (maximum of 38% in 2050) than the one considered with baseline harmonization (28% in 2050). These results show that although common baseline emissions are not the decisive driver for different outcomes they cannot be ignored.

By assuming the same baseline emissions, the models present close results regarding sector abatement, for moderate emission caps. However, as the stringency of the cap increases, the abatement effort and the strategy to reduce emissions differ more.

Although the relevance and usefulness of the models' findings does not rely as much on the accuracy of the numbers as on the insights on how and where climate policies should be applied to meet a GHG cap, the directions pointed out by the two modelling approaches seem to suggest different policy pathways (e.g. allocate higher abatement effort to transport or to industry, or invest more on electricity consumption). By allocating significant emission reductions in one sector instead of other, the models indicate where are the cost-efficient mitigation policy opportunities, influencing for instance the potential for emissions trading. For example, the higher emissions reduction set by TIMES_PT in transports than in industry suggest that is less cost-efficient to reduce industry emissions than transport emissions, which is not the case pointed by GEM-E3_PT.

TIMES_PT main strategy to reduce GHG emissions comparing with BS is to decarbonize the power sector through renewable based technologies, and to shift the end-use sectors' consumption to electricity. These outcomes suggest that the most cost-efficient solution is the adoption of low carbon technologies, which are typically promoted by carbon taxes, financial incentives or regulations..

For GEM-E3_PT the strategy to reduce end-use sectors emissions, rely mainly on energy savings, which is also reflected in the decline of electricity production. This indicates the relevance of demand-side energy efficiency policies as technology or buildings efficiency standards and incentives.

The main difference between the models is related with the transport sector, which currently is responsible for 30% of the GHG emissions in Portugal (APA, 2012). Based on TIMES_PT, transport can play an important role in the economy decarbonization, reducing around 87% from its BS emissions in 2050 for the -60S, thanks to biofuels and high efficient electricity based technologies (electric and hybrid plug-in vehicles). Technology choices are the main driver to GHG abatement, while behaviour changes have a modest contribution, as it is shown in the lower reduction of activity level (Figure 6.4). For GEM-E3_PT, the key driver to transport emissions reduction is the decrease of its energy intensity, achieved by both efficient oil technology options and activity reduction. Therefore, if on one hand policy-makers have results pointing to develop technology oriented policies as incentives for purchasing for example electric vehicles, on the other hand, the conservative vision of the CGE model suggests that road transports will not move away from oil and policies that reduce this activity may be necessary.

Confronted with different results, decision-makers should consider ranges of abatement potentials and costs rather than focus in just one model outcome. It might be reasonable for the policy makers to create incentives for promoting the technological shifts suggested by the BU while taking into account the macroeconomic impacts defined by the TD model(s). However, they are simply tools to explore which technologies and policies could make a specific scenario attainable, and at what possible cost. The model results are just one of the inputs informing the policy decision process, being factors like technology public acceptance as important as its cost-effectiveness. Thus, model outcomes adequacy should be discussed with industry stakeholders, consumer associations, among other.

6.5 Conclusions

This paper aims to assess to what extent two different models (TD and BU) lead to different abatement strategies, while assuming a common Baseline scenario, and how these can result in different domestic climate policy making options. Results show that TIMES_PT and GEM-E3_PT models present close outputs when harmonized to a common Baseline scenario, assigning in general the larger mitigation potential to energy supply. However, the effort level required for each sector, especially for more stringent caps, and the strategy to reduce GHG emissions present dissimilarities which could lead to different policy design. GEM-E3_PT privileges energy efficiency, as it tends to focus more on the demand side, while TIMES_PT relies on the reduction of carbon intensity by shifting energy consumption in end use sectors to electricity and promoting renewable electricity, thus pointing towards incentives to promote low carbon technologies.

Common baseline assumptions cannot be ignored for defining an equal reduction global abatement effort. However, the models characteristics and implicit substitution possibilities are the decisive factor for its different results. The CES function and consumer demand equations in GEM-E3_PT result in a smoother reduction path, while the TIMES-PT reduction path reflects the explicit penetration of technologies ignoring its financial risks or the available capital. These aspects, allied to the fact that TIMES_PT does not include the full economic feedback of GEM-E3_PT also cause the differences in the two models' MAC curves. As described in the literature, the BU TIMES_PT estimates lower costs than the CGE GEM-E3_PT.

The fact that GEM-E3_PT does not include directly renewable energy as TIMES_PT is one of the limitations of this study, although renewable energy consumption is excluded from the results comparison. It should also be underlined that the CGE model can indirectly choose renewable technologies when increasing capital to reduce fossil and electricity consumption. Moreover, as a perfect forecasting model, TIMES_PT anticipate decisions regarding GHG reduction, while, due its recursive dynamic character, the economic agents in GEM-E3 are surprised by the GHG caps. These observations and the fact that the models do not consider the same activity indicators tend to limit its comparison. However, the goal of this paper is not to assess divergences of perfectly comparable models, but rather compare the outcomes of two "real-life" models extensively used in EU climate policy analysis.

Despite its limitations the outcomes from this paper suggest that decision makers should carefully consider which modelling tool is used to support their policies. Climate policy design would ideally be supported by the two modelling approaches, clearly stating the assumptions and limitations associated to each modelling tool. The complementary use of both models could bring added value and result in more robust climate policy making once its specificities make them more appropriate to address certain policy questions. Thus, the CGE model handles better questions on the choice of policy instruments (economic instruments, standards, recycling strategy) while BU models such as TIMES, is more appropriate to evaluate where is more cost efficient to reduce the emissions and which technologies to promote.

Considering the relevance of integrate both modelling approaches in climate policy design, further work is being undertaken to developed a hybrid modelling platform supported by a soft-link between TIMES_PT and GEM-E3_PT, ensuring consistency between its implicit substitution possibilities. This approach has the advantage of being a transparent process, maintaining the integrity of each model and their respective strengths. Assuming the calibration process presented in this paper as a starting point and based on the methodology presented by Labriet et al., (2011), GEM-E3_PT CES function structure will be changed to introduce new energy carriers, and to replicate the energy system profile defined by TIMES_PT, not just for a Baseline scenario but also under different policy scenarios.

6.6 Appendix A

Table A provides a characterization of the models sectors and its correspondence to sectors considered in the calibration process.

Table A – GEM-E3_PT and TIMES_PT sectors and its respective correspondence in the calibration process

GEM-E3_PT productive sectors	TIMES_PT sectors	Calibration sectors
Agriculture	Agriculture	Agriculture
Oil	Oil Refinery	Non electricity energy supply
Coal	Other energy supply	
Natural Gas		
Electricity	Electricity	Electricity
Ferrous and non-ferrous metals	Iron and Steel; Non-ferrous metals	Ferrous and non-ferrous metals
Chemical	Ammonia; Chlorine; Other chemicals	Chemical
Energy intensive sector	Cement; lime; glass; other non-metallic minerals; paper	Energy intensive industries
Electric and Other equipment goods; Transport equipment; Other Industries; Consumer Goods Industries; Food and textile; Construction	Other industries	Other industries
Land transport; Other transport; Households operation of transport associated with Operation of transport (consumption expenditure category)	Transports (road freight, rail freight; buses, Intercity coaches, heavy rail passengers, subway, road car, moto, aviation, navigation)	Transports
Services of credit and insurances; Other Market Services; Non Market Services	Services (space heating and cooling, water heating, cooking, refrigeration, electric appliances, public lighting)	Services
Households Fuels and power associated with Heating and cooking appliances (consumption expenditure category)	Residential (space heating and cooling and water heating, refrigeration, cooking, electric appliances)	Households

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