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

Simões, S.

Citation

Simões, S. (2013, September 4). *Untangling the web : integrating energy and environmental policy instruments by assessing their interactions along power systems*. Retrieved from <https://hdl.handle.net/1887/21628>

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Author: Simões, Sofia

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

Issue Date: 2013-09-04

3 Cost of energy and environmental policy in Portuguese CO2 abatement – scenario analysis to 2020*

* This chapter is published in Energy Policy Journal Vol. 36, Issue 9, pp. 3598-3611. doi:10.1016/j.enpol.2008.06.004. Co-authors: João Cleto, Patrícia Fortes, Júlia Seixas and Gjalt Huppes.

Abstract

This paper quantifies the contribution of Portuguese energy policies for total and marginal CO₂ abatement costs (MAC) for 2020. The TIMES_PT optimisation model was used to derive MAC curves from a set of policy scenarios including one or more of the following policies: ban on nuclear power; ban on new coal power plants without carbon sequestration and storage; incentives to natural gas power plants, and a cap on biomass use. The different MAC shows the policies' effects in the potential for CO₂ abatement. In 2020 in the most encompassing policy scenario, with all current and planned policies, is possible to abate only up to +35% of 1990 emissions at a cost below 23 € t/CO₂. In the more flexible policy scenarios it is possible to abate up to -10% of 1990 emissions below the same cost. The total energy system costs are 10-13% higher if all policies are implemented – 76 to 101 B€ - roughly the equivalent to 2.01-2.65% of the 2005 GDP. Thus, from a CO₂ emission mitigation perspective the existing policies introduce significant inefficiencies, possibly related to other policy goals. The ban on nuclear power is the instrument that has the most significant effect in MAC.

3.1 Introduction

Climate change is currently one of the hot topics in energy and environment policy making. Multiple policy instruments are being developed to address the problem, aiming to coordinate the objectives of climate change mitigation with the ones of the European energy policy: security of supply, competitiveness and sustainability (EU Commission COM(2007) 1 final). Examples include policies promoting renewable energy sources. It is clear that the way forward in European energy policy making includes climate change mitigation. However, it is not clear how policy options made in the past in a different context contribute to this objective. This paper quantifies the significance of the current Portuguese energy policies for the national CO₂ marginal abatement costs (MAC) for 2020. The results can be of utmost relevance for shaping cost-effective energy and climate change policies, avoiding unnecessary costs

Portugal has assumed the commitment to limit its greenhouse gases (GHG) emissions below +27% of 1990 levels under the Kyoto Protocol and the EU Burden-Sharing Agreement. In 1990 60 779¹⁷ Gg CO₂e were emitted, and thus 77 391 Gg CO₂e per year are allowed in 2010-2012 (IA, 2006b). However, the Portuguese GHG emissions have been increasing sharply and the country is far from its goal: the 2010 emissions estimated are 45-48% above 1990 levels if no additional mitigation policies are adopted (IA, 2006a). CO₂ emissions from energy consumption and industrial processes are approximately 71% of total national 1990 emissions and are expected to grow in 2010 up to 80% of total national emissions (IA, 2006a).

This is due to the high national dependency of imported fossil fuels, mostly oil. In 2005 about 84% of the national primary energy demand of 1 132 PJ was met by imported oil, coal and gas (DGGE, 2007). Renewables are the only national energy resources, especially hydro for power generation, and biomass used both in cogeneration and in the residential sector. Transport and industry bear the lion share of the national final energy demand, with 44% and 26% respectively of total final energy demand in 2005. Electricity generation is also highly dependant of imported coal, gas and oil which

¹⁷ Including Land Use, Land-Use Change and Forestry.

accounted for 65-83% of generated electricity in the 1999-2007. Renewables are responsible for the rest of generated electricity, especially hydro which accounted for 39-11% of total electricity generated in 1999-2007. The other renewable power sources are wind and biomass (respectively 20% and 16% of 2007 renewable electricity) (DGGE, 2007a). Nuclear power is not used and is considered politically unacceptable by the several governments so far. Aware of the diverse fragilities of the national energy system, the national energy policy is based on three strategic goals: energy security, sustainable development and national competitiveness (Cabinet Resolution no. 169/2005).

Among the myriad of energy and environmental policies in place the following are considered as the most relevant regarding effects on CO₂ emissions for the 2010-2020 period: i) ban on nuclear power; ii) incentives to the distribution and licensing of natural gas power plants; iii) feed-in-tariffs to promote renewable electricity; iv) minimum consumption of biofuels of 5.75% of the consumed diesel and gasoline in transport in 2010, following the Directive 2003/30/EC; and last but not the least, the CO₂ emission cap following the EU burden sharing agreement.

All these instruments have an impact in the national energy system, which in this paper is quantified in terms of total and marginal abatement cost (MAC) for CO₂ emissions. The knowledge of the cost of reducing an additional unit of CO₂ is fundamental to define the emissions reduction potential within a feasible cost range, and thus to support the development of emission control policies. MAC on CO₂ for Portugal have been estimated by several global and multiregional models (e.g. POLES, PRIMES, TIMER, GAINS). However, in these studies the Portuguese curves are not public and the analysis does not assess the impact of existing policies (Das *et al.*, 2007; Russ and Criqui, 2007; Capros and Mantzos, 1999; EEA, 2005; den Elzen, *et al.*, 2007; Klaassen, *et al.*, 2005). The objective of this paper is twofold: to present the marginal abatement costs curve for CO₂ emissions for the Portuguese energy system in 2020, and to quantify the impact of the current Portuguese policy instruments on marginal and total cost. For this, a set of alternative policy scenarios, including different combinations of the existing policies are modelled in the bottom-up optimization model TIMES_PT for the 2000-2030 period.

The paper starts by presenting an overview of the TIMES_PT model. Next, the modelled energy scenarios are described, prior to the presentation of the results regarding impact of the planned and existing policies on CO₂ MAC curves, total system costs, primary and final energy consumption, and sector abatement. The validity of the results is assessed through a sensitivity analysis. The significance of the studied policy instruments and limitations of the results are discussed in the concluding section.

3.2 TIMES_PT model

TIMES_PT¹⁸ is a linear optimisation bottom-up technology model generated with TIMES¹⁹ model generator. TIMES was developed by ETSAP²⁰ of the International Energy Agency. The generic model structure can be adapted to simulate a particular energy system, which may be local, national or multi regional. TIMES models are widely used to evaluate the impact of energy and environment policies and to perform technological assessments (Tosato, 2006).

The ultimate objective of a TIMES model is the satisfaction of the energy services demand at the minimum system cost. For this, TIMES simultaneously decides on equipment investment and operation, primary energy supply and energy trade, according to the equation 1 (Loulou *et al*, 2005a).

¹⁸ The implementation of the TIMES model for Portugal has been undertaken within the EU FP7 research project NEEDS – New Energy Externalities Developments for Sustainability (www.needs-project.org). The NEEDS RS2a research team is responsible for the model structure and new technologies databases. The authors are responsible for the base-year information, for the validation of technologies information, and for calibration and validation of the national model.

¹⁹ Acronym for The Integrated MARKAL-EFOM system. TIMES is the successor of two older ETSAP bottom-up energy models: Markal - MARKet Allocation Model and EFOM - Energy Flow Optimisation Model, developed in the 80's.

²⁰ Energy Technology Systems Analysis Programme

$$NPV = \sum_{r=1}^R \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} \bullet ANNCOST(r, y) \quad (1)$$

NPV: net present value of the total costs

ANNCOST: Total annual cost

d: general discount rate

r: region

y: years

REFYR: reference year for discounting

YEARS: set of years for which there are costs²¹

For each year, the TIMES model computes the discounted sum of the annual costs minus revenues. In the case of TIMES_PT, both investment costs and fix and variable operation and maintenance costs of the energy supply and demand technologies are considered. Energy taxes are also included in the model, namely the ISP which is the tax on oil products and other energy carriers and is differentiated by energy carrier. The revenues usually considered within TIMES models include subsidies, recuperation of sunken material and salvage value. However, these are not included in TIMES_PT. More information on TIMES development and equations can be found in Loulou *et al* (2005a and 2005b).

3.2.1 TIMES_PT Model structure

TIMES_PT represents the Portuguese energy system from 2000 to 2030. The following sectors are modelled: primary energy supply; electricity generation; industry; residential; commercial; agriculture, and transport. Energy, materials and monetary flows, energy demand and supply technologies are modelled in detail, including mass balances. The model structure for the

²¹ All years in the horizon + past years if costs have been defined for past investments + a number of years after the life time of the technology if some investment and dismantling cost are still being incurred, as well as the Salvage Value.

Portuguese system, presented in Figure 3.1, was adjusted from the model structure developed under the NEEDS²² project.

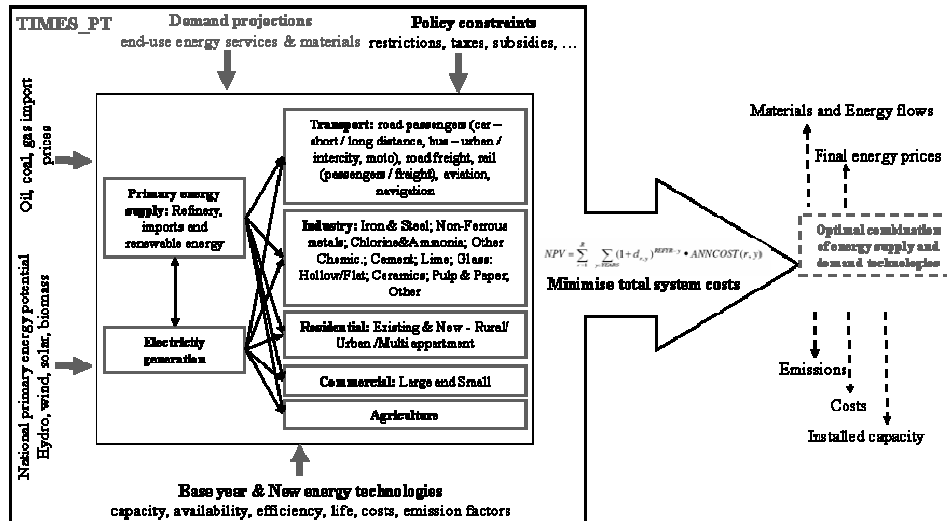


Figure 3.1. Structure of the TIMES_PT model.

The implementation of TIMES_PT is supported by a detailed database, with the following exogenous inputs: (1) *end-use energy services and materials demands*, such as residential lighting, machine drive requirements or steel; (2) characteristics of the existing and future *energy related technologies*, such as efficiency, stock, availability, investment costs, operation and maintenance costs, or discount rate; (3) present and future *sources of primary energy supply* and their potentials; and (4) *policy constraints*, such as emission ceilings or energy taxes.

The TIMES_PT model finds the optimum combination of energy supply and demand technologies to satisfy the demand, i.e. the model designs an energy system with the lowest possible total costs. Thus, the main model outputs include the installed capacity of the different technologies, its greenhouse gas

²² NEEDS – New Energy Externalities Developments for Sustainability (www.needs-project.org)

emissions, primary and final energy and material flows, final energy prices and, as mentioned, overall system costs.

It should be noted that TIMES_PT is a partial equilibrium model, and thus does not model the economic interactions outside of the energy sector. Among other limitations of these types of models, it does not assume technology R&D costs nor considers in detail demand curves and non-rational aspects that condition investment in new, more efficient technologies, such as preferences motivated by aesthetics or social status. The model assumes that stakeholders have perfect market foresight.

3.2.2 Energy and materials demand projection

The materials and energy demand projections for Portugal are differentiated according to economic sector and end-use energy service. These were generated by the national macroeconomic projections from the GEM-E3²³ model within the NEEDS project. For a EU-22 GDP growth target of 2 to 2.5% - depending on the country - GEM-E3 combines projections of population growth, world energy prices, technical progress, energy intensity and labour productivity evolution, generating a series of national macroeconomic drivers. These are: GDP growth; private consumption as a proxy for disposable income; price evolution and sector production growth for industry, services, transports and agriculture. In TIMES_PT, these macroeconomic drivers are transformed into the different final annual end-use demand projections (DEM_t), according to equation 2 (adapted from van Regemorter and Kanudia, 2006),

$$DEM_t = DEM_{t-1} * (1 + DRGR_t * ELASI) * (1 + PRGR_t * ELASP) * (1 - AEEi_t) \quad (2)$$

DEM – Final demand (materials or end-use energy)

DRGR - Macroeconomic drivers

²³ GEM-E3: General Equilibrium Model for Energy-Economy-Environment: <http://www.gem-e3.net/>

ELASI and ELASP – income and price elasticity of final demand to DGDR provided by Leuven University²⁴

PRGR – price evolution factor from GEM-E3

AEE_i - autonomous efficiency improvement factor in industry from GEM-E3

The residential sector requires a more detailed approach to generate the demand for heat, cooling and hot water, since they depend on the characteristics of the dwellings. Figure 3.2 illustrates the approach to deal with the residential sector demand for energy end uses, following the NEEDS framework (van Regemorter and Kanudia, 2006). The projection of energy end-uses for the residential sector involved several steps: (1) the projection of the number of dwellings and its allocation by category (rural, urban single house or urban apartments); (2) the projection of the heat/cooling/hot water demand per dwelling by category, and (3) the projection of the total demand. The main data sources were the National Directorate for Energy and Geology (DGGE, 1996), the National Statistics Institute (INE 2000a; INE, 2001; INE, 2002; INE, 2003; INE, 2004), and the SIAM Project²⁵ (Aguiar *et al.*, 2002).

²⁴ Energy, Transport & Environment Working Group of the CES - Department of Economics of the Leuven Catholic University:
<http://www.econ.kuleuven.be/ew/academic/energmil/default.htm>

²⁵ The SIAM project stands for Climate Change in Portugal: Scenarios, Impacts and Adaptation Measures. More information can be found at:
<http://www.siam.fc.ul.pt/overview.html>

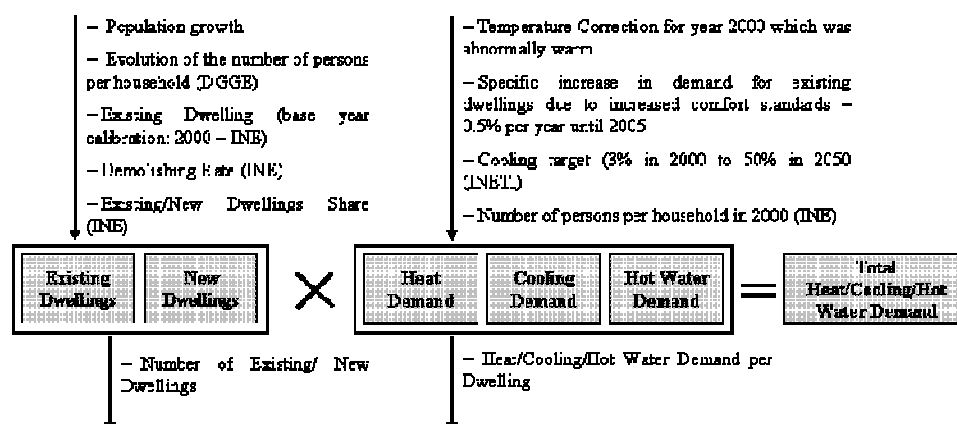


Figure 3.2. Projection of the demand in the residential sector for hot water, heating and cooling.

The GEM-E3 macroeconomic drivers were validated through its comparison with national demographic, macroeconomic, and sector scenarios, which was complemented by an extensive stakeholder consultation process. Major adjustments were made in the transport and commercial sectors for which the GEM-E3 generated projections were replaced by those provided by the National Climate Change Programme (PNAC) demand (IA, 2006a). Some of the final energy and material demand growth trends considered in TIMES_PT are presented in Table 3.1.

Table 3.1. Evolution of the population, GDP and demand for some of the end-use energy services and materials considered in TIMES_PT (2000 = 100).

Type of demand/year	2000	2005	2010	2015	2020	2025	2030
Population	100	103	105	105	105	105	104
GDP	100	105	118	132	145	160	175
pkm	100	103	109	113	117	120	124
tkm	100	101	118	129	137	145	153
Space Heating	100	127	132	136	137	139	140
Space Cooling	100	159	203	252	294	336	382
Water Heating	100	103	111	117	120	122	124
Clinker	100	101	113	121	127	133	140
Glass	100	101	115	123	131	138	145
Pulp	100	97	106	109	111	112	114
Iron & Steel	100	98	103	104	104	104	103

3.2.3 Other exogenous information inputs

A detailed explanation of the other exogenous information inputs, especially regarding the technology database, can be found in the appendix. Here is just briefly mentioned the most relevant aspects, namely:

- *Carbon capture and storage* is considered assuming a storage potential of in TIMES_PT in a simplified way due to the lack of information on the storage potential for Portugal and neighbouring countries. Thus, a conservative estimate of 5000 Gg CO₂/year storage potential is assumed available from 2015 onwards. This corresponds to 6% of the emissions modelled in TIMES_PT in 2020, according to PNAC (IA, 2006a). This potential has a great uncertainty, which was dealt with a sensitivity analysis, described in the results section.

- Average *primary energy imports prices* projections were adopted from DG TREN and IEA scenarios, namely 1.35-1.75 €₂₀₀₀/GJ for coal, 6.51-5.79 €₂₀₀₀/GJ for crude oil, and 3.84-4.60 €₂₀₀₀/GJ for natural gas, respectively for 2000 and 2020 (DGTREN, 2006). TIMES_PT does not consider the effects of extreme situations, such as oil price peaks due to political instability or natural catastrophes. Uranium fuel prices, as UO₂ reactor fuel at the power plant, are of 0.4 €₂₀₀₀/GJ and kept constant in time, as suggested by the IEA (2001).

- The model considers long term *price elasticity of demand* for the different materials and energy end-uses (Loulou *et al.* 2005a).

- The definition of national primary energy potentials - essentially renewable resources such as water, solar, wind, biomass and biofuels - was based on several national studies and expert opinion (Table 3.2). It should be stressed that there is a large uncertainty due to the lack of data for some cases. Uncertainty on hydro potential was dealt with via a sensitivity analysis.

- TIMES_PT uses a homogeneous discount rate of 4% which is not differentiated between sectors.

Table 3.2. National Primary Energy potentials considered in TIMES_PT.

Primary Energy	Used in 2000 →Potential in 2030 (% increase from 2000 to 2030)	Reference
Wood products (PJ)	71.7→100 (+28%)	Expert opinion
Biogas production (PJ)	0.1→29 (+100%)	GPPAA- MADRP (2005) and extrapolation of National Climate Change Waste Management Scenarios (IA, 2006a)
Crops for biofuel production (PJ)	0.0→15 (+100%)	Extrapolation based on Gonçalves, H., Joyce, A., Silva, L. (eds) (2002c)
Biofuels production (PJ)	0.0→50 (+100%)	Expert opinion based on 2008 expected installed capacity
Municipal Waste (PJ)	7.3→10 (+27%)	Extrapolation of National Climate Change Waste Management Scenarios (IA, 2006a)
Industrial Waste - Sludge production (PJ)	0.0→2 (+100%)	Expert opinion
Hydro (PJ)	40.2→95 (+58%)	Pinho, M. (2007)
Wind off shore (GW)	0.0→2 (+100%)	Expert opinion
Wind on-shore (GW)	0.1→5 (+98%)	2010: Estanqueiro, I. (2004) and 2030: conservative Assumption based on Pinho, P. (2007)
Solar- water and space heating (PJ)	0.8→38 (+98%)	Gonçalves, H., Joyce, A., Silva, L. (eds), 2002b
Solar thermal - electricity generation (GW)	0.0→2 (+100%)	Expert opinion
Geothermal (PJ)	0.6→8 (+93%)	Extrapolation based on Gonçalves, H., Joyce, A., Silva, L. (eds), 2002a
Waves (GW)	0.0→5 (+100%)	Cruz, J., Sarmiento, A. (2004)

3.2.4 Calibration and validation

The model was calibrated for the year 2000 and validated for 2000 and 2005, using the official national energy balances. Model calibration required a set of restrictions:

1. To replicate real evolution of electricity imports and exports - affected by interconnection capacity with Spain - increasing maximum limits were set from 2000 to 2030, up to a maximum import and export of 46 and 20 PJ in 2020, respectively, and of 60 and 30 PJ in 2030. These are estimates since there are no exact forecasts at the moment, although they are in line with the national transmission operator studies (REN, 2008). This corresponds to a growth of imports of 255% and of 121% for exports. Thus, trade uncertainty under the liberalised Iberian electricity market is not considered;
2. A maximum growth was set for new CHP plants in industry, based on historical data and on the sector (national CHP association) future expectations. Thus, in 2001, 32% of all electricity consumed in industry was from CHP, and in 2010 this figure will be 38%, 45% in 2020 and 50% in 2030. These limitations on maximum CHP reflect real CHP constraints such as geographical proximity of potential end-users of heat;
3. Following the past evolution of the energy profile of the residential, commercial and agriculture, there will be no further penetration of coal in these sectors;
4. Due to resistance to change, imperfect information, and aesthetics or other subjective preferences it is assumed that the penetration rate of new technologies with alternative fuels in the residential and commercial sectors is delayed by inertia factors. These were defined for the replacement of existing lighting and electric appliances and for existing biomass, LPG and diesel technologies for cooking, space heating, and water heating by new more efficient alternatives, but using the same fuels;"
5. Only 85% of the residential and commercial sector needs can be met with natural gas, due to geographic and technical limitations (GALP, 2007);
6. No dedicated heat power plants will be implemented – all heat will be produced with CHP - and all new CHP plants are associated with specific demand sectors such as refining, industry, commercial or residential. This follows the current and planned CHP promoting policy.

3.3 Energy and environment policy scenarios

Six energy and environment policy scenarios were considered to assess the contribution of existing policies in the CO₂ MAC curves for 2020. The difference between scenarios is the level of implementation of existing Portuguese energy policies until December 2005. The reference scenario, hereafter mentioned as policy scenario, considers the most relevant Portuguese energy policies in place, as follows:

1. A ban on nuclear power due to the political unacceptability of this option in the modelled time horizon;
2. Incentives to natural gas combined cycle power plants following the energy sources diversification policy and support to use of natural gas. This is modelled as a minimum installed capacity of at least 1100 MW from 2010 to 2030;
3. New coal power plants will only be available from 2015 onwards following energy sources diversification policy and support to use of natural gas;
4. It is assumed that “conventional” coal power plants without sequestration will not be implemented from 2015 onwards, following expected GHG control policies;
5. Electricity generation from municipal waste will continue until 2030 following present waste management policy which sets a minimum target for energetic use that corresponds approximately to 3.01 TWh generated electricity in 2020 and 2030(IA, 2006a);
6. Electricity generation from wood residues will continue at least until the end of the lifetime of plants existing in the year 2000 following forest fire control policies objectives;
7. A minimum of 1.1 GW installed capacity of wind onshore is set up in 2005, following the existing feed-in-tariffs for renewable electricity, although this is not included in the costs of renewable electricity generation technologies in TIMES_PT. This represents 9% of total 2005 installed capacity of 13.55 GW;
8. In 2010 biofuels consumption will be at least 5.75% of the consumed diesel and gasoline in transport, following the Directive 2003/30/EC;

9. The tax on oil products, differentiated according to the energy carriers, was included, as presented in Table 3.3.

The other studied five alternative policy scenarios are identical to the policy scenario except for the level of implementation of some of the assumed policies, as follows and as summarised in Table 3.4:

1. No policy – excludes all policies assumed in the policy scenario;
2. Nuclear – policy scenario allowing nuclear power. Because Portugal has no nuclear power plants at the moment it is assumed that such plants will only be operating from 2015 onwards, since it is considered that at least 8 years will be necessary to select a site, train personnel and obtain the necessary permits;
3. Conventional coal – policy scenario allowing conventional new coal power plants;
4. No incentives to gas – policy scenario without incentives for combined cycle natural gas power plants;
5. No biomass – policy scenario with a cap on biomass domestic production and imports, which does not allow for biofuel production. The cap was set at 2005 levels the most recent value on total national biomass consumption. The limit is set for wood and wood waste and for biofuels. This represents roughly 60% of the available national wood potential until 2020 and 4% of the biofuels potential assumed in **Error! Reference source not found..** This scenario does not correspond to one explicit current energy policy, but was studied since future national policies point towards an increased used of biomass for biofuels production and electricity generation. The objective is to assess what is the effect in MAC if biomass is not available in the expected quantities.

Table 3.3. Tax on energy products considered in TIMES_PT in €/PJ.

Energy carriers	Tax on energy products (€/PJ)		
	2001	2005	2010-2030
Coal – RCA, supply & industry	-	0.15	0.16
Coal – electricity & CHP	-	-	-

Energy carriers	Tax on energy products (€/PJ)		
	2001	2005	2010-2030
Oil– residential & commercial	6.68	2.48	3.73
Oil – electricity & CHP	-	-	-
Oil - agriculture	1.63	2.11	2.78
Oil - industry	0.69	0.38	0.38
Gas – RCA ^a , supply & industry	0.20	-	-
Gas – electricity & CHP	-	-	-
Gas - transport	0.20	2.60	2.72
LPG – RCA & industry	0.16	1.58	0.69
LPG - transport	8.70	4.52	6.82
Diesel - agriculture	8.98	11.48	14.22
Diesel - transport	6.68	8.54	10.58
Gasoline - transport	11.46	18.04	20.57
Biofuels ²⁰ - transport	8.98	11.48	14.22
Kerosene – transport	-	-	-
Heavy fuel oil - transport	-	-	-
Naphtha - industry	-	-	-
Biomass – all sectors	-	-	-
Electricity – all sectors	-	-	-

^a RCA stands for Residential, Commercial and Agriculture.

Increasingly strict CO₂ emissions caps were set for each of the six policy scenarios to build the marginal abatement cost curves for CO₂ emissions for 2020. The caps are constant for the 2020-2030 period and range from a maximum increase of CO₂ emissions of 90% (91 141 Gg CO₂) compared to 1990 levels, to a maximum decrease of 60% (19 188 Gg CO₂). Besides the CO₂ cap for 2020 to 2030, all scenarios consider the Portuguese commitment under the Kyoto Protocol (and the EU burden sharing agreement), which corresponds to an increase of 27% of 1990 emissions in the first commitment period of 2008-2012 ²⁷.

²⁶ Biodiesel, ethanol, methanol

²⁷ This obligation was implemented in the TIMES_PT model as a cap of 63 344 Gg CO₂ from 2010 to 2015. This cap value corresponds to 80% of the one fifth national assigned amount (77 391 Gg CO₂e) (IA, 2006b), because only approximately 80% of national total emissions are included in the model. TIMES_PT deals exclusively with emissions from combustion and productive processes which account for approximately for 80% of national emissions in 2010 (IA, 2006a). The following GHG emissions sources are not considered in

Table 3.4. Studied policy scenarios and respective policy restrictions.

	Policy	No Policy	Nuclear	Conventional coal	No incentives to gas	No biomass
Ban on nuclear power	✓			✓	✓	✓
Incentives to natural gas power plants	✓		✓	✓		✓
New Coal power plants only after 2015	✓		✓	✓	✓	✓
CCS obligatory for coal power plants after 2015	✓		✓		✓	✓
Electricity from waste and wood waste continued till 2030	✓		✓	✓	✓	✓
Minimum wind installed capacity in 2005	✓		✓	✓	✓	✓
Biofuels >5.75% in transport fuel after 2010	✓		✓	✓	✓	
Tax on oil products	✓		✓	✓	✓	✓
Cap on biomass						✓

CO₂ emission trading is not considered in any of the policy scenarios; neither the EU scheme nor the Kyoto protocol one or the other Kyoto flexible mechanisms. This does not hinder the results, since the main objective is to study changes in the national internal CO₂ MAC curves.

3.4 Results and discussion

3.4.1 Marginal abatement cost curve

The CO₂ MAC curves for 2020 for Portugal obtained with TIMES_PT for the six policy scenarios are presented in Table 3.5 and Figures 3.3 and 3.5. The effect of the policies in MAC curves is assessed in two complementary ways: 1) comparing MAC for the same reduction effort vis-à-vis 1990 emissions, i.e.

the model and in this paper: from solvents use, non-combustion agricultural activities, waste management, fugitive emissions from fuels and f-gases. The Kyoto cap value also considers 80% of the sinks capacity (2 698.79 GgCO₂/year) (IA, 2006a) which is kept constant until 2030, with a CO₂ removal cost of 5.5 €/t CO₂ (NEEDS Technology Database).

the same CO₂ emissions cap (Figure 3.3), and 2) assessing the motives for the “leaps” in the MAC curves using the classic MAC chart, which plots MAC per abated tonne of CO₂ (Figure 3.5). In this paper differences in MAC are primarily assessed for identical emission caps because this approach better conveys the involved abatement effort, a decisive criterion for policy making.

The introduction of policies significantly increases MAC: the policy scenario has 91 to 42% higher costs than the no policy scenario, respectively for the emission caps of +20% and -60% CO₂ from 1990 levels. The ban on nuclear power is the most important policy influencing costs of marginal CO₂ abatement, as the MAC of the nuclear scenario are similar to the no policy scenario and much lower than for the policy scenario (87 to 29% less for the 0 and -60% caps). The MAC of the other intermediate policy scenarios (no incentives to gas, conventional coal and no biomass) are much closer to the policy scenario and roughly follow the same curve (Table 3.5).

Table 3.5. Marginal abatement costs and abated CO₂ for the six policy scenarios for the +40% to -60% CO₂ emission caps.

%change/ 1990	Policy		No Policy		Nuclear		Conventional coal		No incentives to gas		No biomass	
	Abated Gg CO ₂	MAC €/tCO ₂	Abated Gg CO ₂	MAC €/tCO ₂	Abated Gg CO ₂	MAC €/tCO ₂	Abated Gg CO ₂	MAC €/tCO ₂	Abated Gg CO ₂	MAC €/tCO ₂	Abated Gg CO ₂	MAC €/tCO ₂
+40%	5266	5	0		0		25737	10	4749	5	8575	27
+30%	10326	33	0		0		30798	27	9810	29	13636	37
+20%	14859	37	1300	3	0		35331	37	14343	38	18169	38
+10%	19656	38	6097	8	0		40128	38	19140	39	22965	39
0%	24453	42	10894	14	4057	5	44925	59	23937	42	27762	68
-10%	29250	93	20488	24	8854	31	49722	105	28733	61	32559	99
-20%	34047	120	25285	57	13651	65	54518	129	33530	146	37356	226
-30%	38844	256	30082	127	18448	123	59315	246	38327	252	42153	353
-40%	43641	464	15691	209	23245	261	64112	437	43124	445	46950	625
-50%	48437	754	34879	362	28041	584	68909	724	47921	769	51747	1070
-60%	53234	1460	39676	851	32838	1038	73706	1516	52718	1516	56544	1830

Thus, there are two groups of scenarios regarding MAC behaviour: with and without nuclear power. Figure 3.3 plots the 2020 MAC with % of emission reduction from 1990 levels (or emission increase, represented with a negative sign), up to a maximum MAC of 130 €/t CO₂. As explained in section 3.3, it was estimated that approximately 47 969 Gg CO₂ were emitted in 1990 from combustion and industrial processes activities modelled in TIMES_PT. Without any emission cap, the emissions of the no policy and nuclear scenarios are respectively 58 863 and 52 026 Gg CO₂ which corresponds to a 23% and 8% increase of the 1990 emissions modelled in TIMES_PT. The scenarios without nuclear have much higher no-cap emissions: 94% of 1990 emissions for the conventional coal scenario (92 893 Gg CO₂), 58% for the no biomass scenario (75 731 Gg CO₂), 51% for the policy scenario (72 422 Gg CO₂) and 51% for the no incentives to gas scenarios (71 905 Gg CO₂).

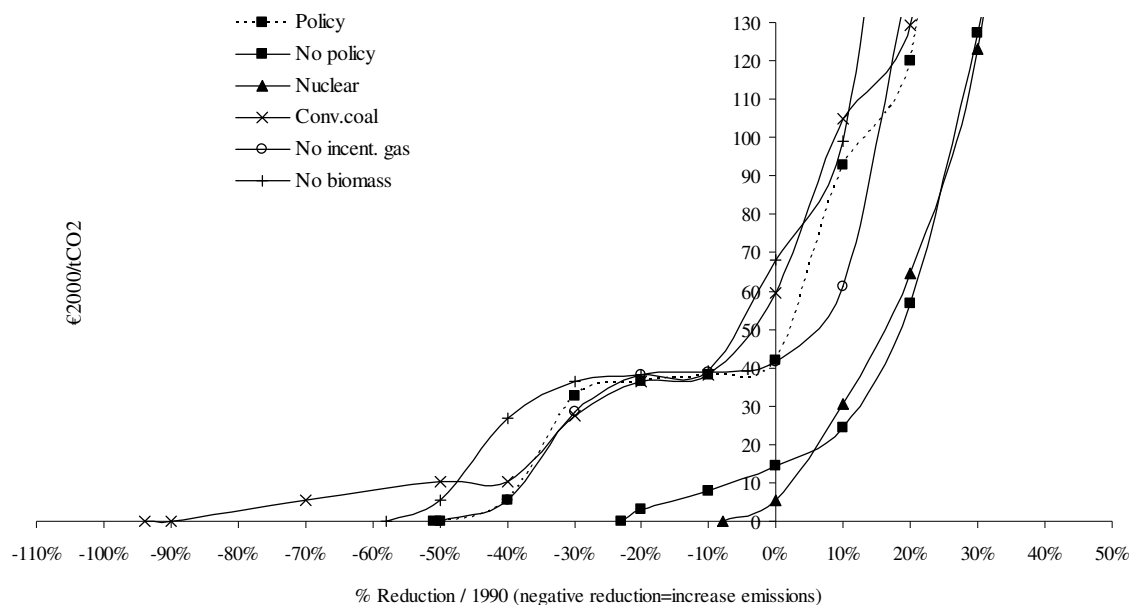


Figure 3.3. Marginal abatement costs curves for the Portuguese energy system in 2020, as % reduction from 1990 levels (the negative sign corresponds to an increase in emissions).

The two scenarios with nuclear power have cheaper MAC as nuclear plays a major role in electricity generation (Figure 3.4). When allowed, the share of electricity generated from nuclear is never less than 71% of generated

electricity; roughly to 8.5 GW installed capacity. Such quantities of nuclear power are very likely unfeasible in Portugal due to other concerns than global warming, such as size of the territory and energy security issues. Moreover, because there is no national specific data on waste management costs, these were not included in the model, which could have made nuclear less competitive. Nonetheless, it is useful to assess the maximum reduction in CO₂ emissions and MAC that could be obtained with nuclear power. The differences in the MAC of the nuclear and no policy scenario occur because in the latter electricity is also generated from conventional CHP coal power plants, which are banned in the nuclear scenario and replaced by gas, due to the modelled incentives.

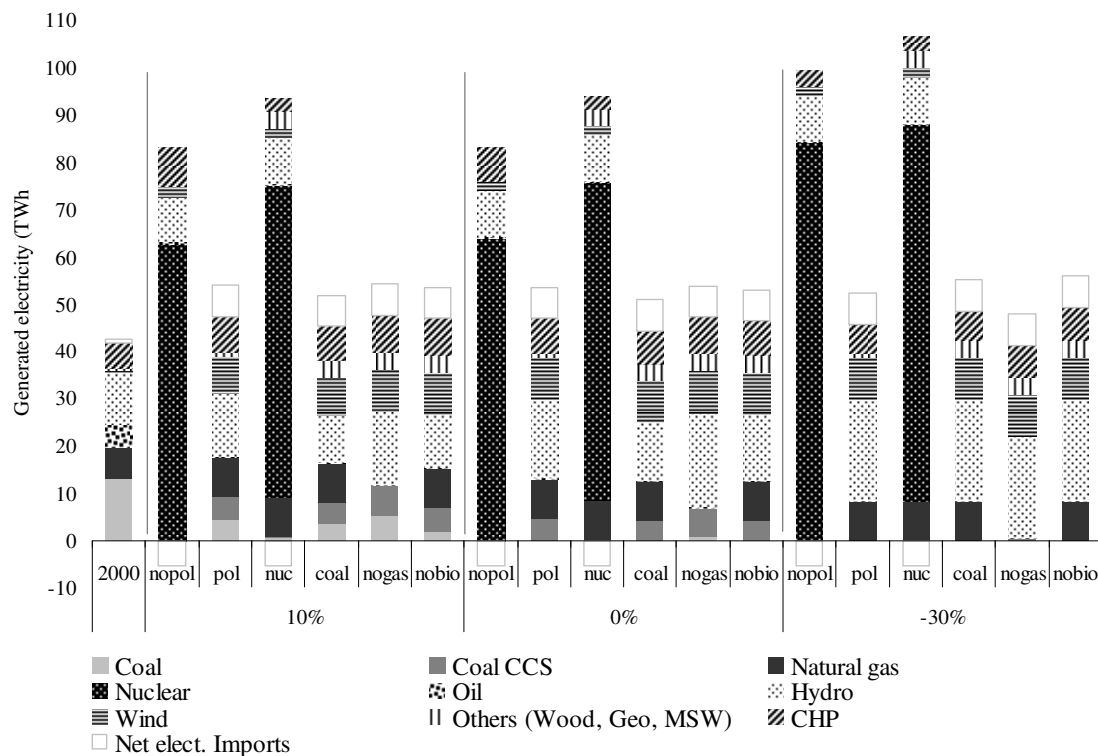


Figure 3.4. Electricity generated in 2020 for the six policy scenarios: nopol - no policy; pol – policy; nuc –nuclear; coal – conventional coal; nogas – no incentives to gas; nobio – no biomass.

In the scenarios without nuclear power the effects in MAC are less significant (differences in MAC below 20%). In fact, for “moderate” CO₂ emission caps of 30% to 10% increase from 1990 these three policy scenarios do not significantly affect MAC (maximum difference of 17% vis-à-vis the policy

scenario). These caps are the most probable ceilings following the EU effort sharing negotiation. The biomass limit is the most important policy assumption affecting MAC curves, followed by the ban on conventional coal power plants. The effect of the incentives to gas is less significant, as the no incentives to gas MAC curve follows closely the policy MAC curve except for the -10% and -20% caps.

The limit on biomass increases MAC from 3 to 89% compared to the policy scenario for the +10% to -20% caps because cheap abatement options switching from fossil fuels to biomass (including biofuels) are limited. However, this does not have a significant effect for “moderate” emission caps above 0% (the increase in MAC is less than 11%) when biomass is not playing an important role yet. For such moderate restrictions abatement is achieved primarily by the electricity generation sector for which there is a broad variety of cheap abatement options besides biomass use. For more restrictive CO₂ caps the no biomass scenario MAC become significantly higher (more than 20%) than in the policy scenario, as abatement has to be done by other sectors where biomass plays an important role: industry and residential. In the no biomass scenario biomass is practically all used in the electricity and residential sectors, whereas in the policy scenario biomass use is distributed across all sectors. Thus, for Portugal the use of biofuels in transport aiming to reduce CO₂ emissions is only a cost effective policy for emission caps identical to 1990 levels and beyond.

The ban on conventional coal power plants only has significant effects for emission caps less restrictive than +30% and for the 0% cap. For other caps, differences in MAC of the conventional coal and policy scenarios are below 20%. The ban mostly reduces MAC and thus the policy MAC is lower than the conventional scenario MAC. The exception is the +30% cap for which the policy MAC is 17% higher than the conventional coal scenario. For the other two significantly different caps the MAC of the policy scenario is 88% less in the +40% cap and 41% less for the 0% cap. The differences in MAC between the conventional coal and policy scenarios have two different causes: 1) penetration of very polluting coal gasification plants up to the +30% cap²⁸

²⁸ Up to the +30% cap the ban on conventional coal of the policy scenario leads to a higher penetration of very polluting coal gasification plants that produce methanol and DME

and 2) penetration of conventional coal power plants for the 0% cap and beyond. Therefore, in the conventional coal scenario earlier CO₂ abatement is achieved by reducing the activity of the conventional coal power plants, which is more expensive than stopping the use of coal gasification plants done in the other scenarios. For the +30% cap onwards coal gasification does not occur in any scenario and the conventional coal penetration is anyhow limited by the emission cap, thus levelling abatement options across scenarios. The leap in the MAC curve of the conventional coal scenario for the 0% cap onwards is due to the complete shutdown of conventional coal plants.

The incentives to gas scenario both contributes to increase or decrease MAC, depending on the emission cap, but the variations are less than 20% except for the -10% and -20% caps. In the first case the incentives to gas increase MAC in 34% because cheap abatement switching from coal to gas is less available in the policy scenario. In the -20% cap the incentives to gas decrease MAC in 21% because in the policy scenario it is still possible to replace combined cycle gas power plants with hydro, gas plants with CCS and hydrogen fuel cell CHP. Maximum hydro was installed earlier in the no incentives to gas scenario and thus only more expensive hydrogen CHP are now available.

Figure 3.5 plots the 2020 MAC against abated CO₂. As explained before the starting point of the curve - emissions without any cap - is different for the six policy scenarios, which leads to a different assessment of MAC than in Figure 3.3. For example, a 10 000 Gg²⁹ CO₂ abatement has a MAC of 5 €/t CO₂ for the conventional coal scenario, of 13 €/t CO₂ for the no policy, 30-31 €/t CO₂

used in the transport sector. When conventional coal power plants are allowed, practically all coal is used to generate electricity, since conventional coal power plants are cheaper than coal gasification. This happens because there is a limited amount of cheap coal available. When conventional coal power plants are not allowed, electricity generation from coal has to be done with coal CCS plants which are 0.38-0.72 €/cents/kWh more expensive than conventional coal plants (37-69% more expensive), and 12% less efficient. This cost and efficiency differences are enough to make coal gasification competitive in the scenarios with the ban on conventional coal.

²⁹ The abated CO₂ is estimated for each policy scenario relatively to its no cap emissions in 2020.

for the policy, no incentives to gas and no biomass scenarios, and 39 €/t CO₂ for the nuclear scenario. However, this does not give any indication of the corresponding very different effort level compared to 1990 emissions: the 10 000 Gg abatement roughly corresponds to a 60% increase in emissions from 1990 levels for the conventional coal scenario, but only half than that for the policy, no biomass and no incentives to gas scenarios. The 9 €/t CO₂ difference between the MAC of these three scenarios and the nuclear scenario corresponds to the abatement of the same 10 000 Gg CO₂, but for the first three this represents a 30% increase from 1990 levels, whereas it is a 10% reduction for the nuclear scenario. Because the effort level was chosen as the comparison criteria for MAC, this figure is here only used to identify leaps in MAC curves for each of the scenarios, which correspond to the adoption of new technologies.

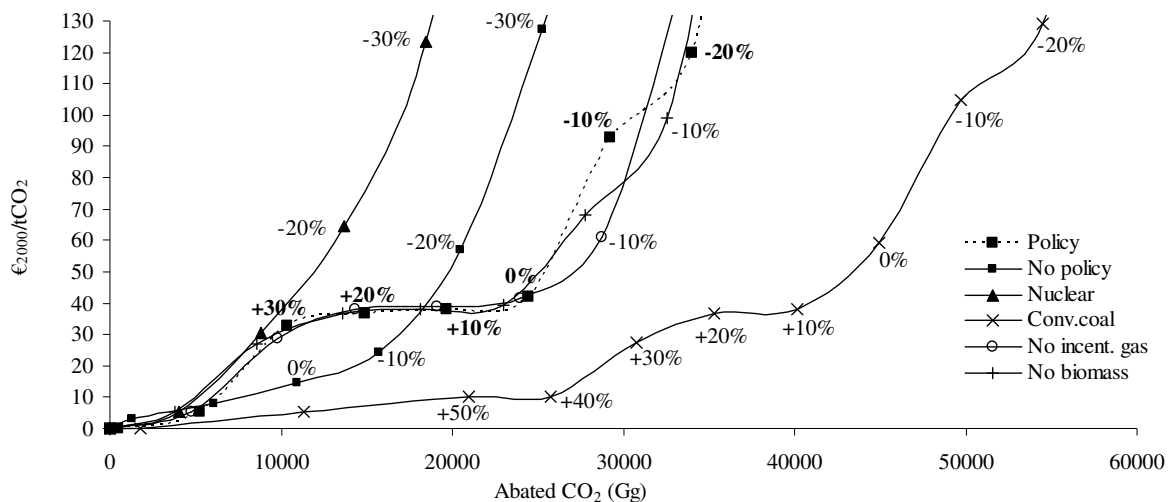


Figure 3.5. Marginal abatement costs for Portugal in 2020. The % values are the CO₂ emission caps compared to 1990 emissions (positive = increase in emissions). The start of each MAC curve corresponds to different CO₂ emission caps since the emissions when there is no cap are also different.

In the policy, no biomass and no incentives to gas scenarios there are two points in which MAC increases sharply: for emissions reductions above 5 000 Gg, from 5.45 to 32.81 €/tCO₂, and for reductions above 25 000 Gg, from 42.09 to 92.92 €/tCO₂. The first “leap” in the MAC curve is mainly due to

reductions stopping coal gasification plants, in CHP, electricity generation, and to a less extent, in industry. Reductions are achieved reducing the use of conventional coal and substituting heavy fuel oil CHP plants and boilers by gas ones. The second leap is due to reductions in the same sectors but industry plays a more important role. The abatement is achieved by further reductions of fuel oil CHP plants, which are substituted by a large CHP coal plant with CCS. In the industry sector year 2000 boilers have practically disappeared and more advanced kilns are installed. In the electricity generation sector a new gas combined cycle plant with CCS is installed. At this point, plants that operated in the year 2000 are practically not functioning and hydrogen generation from solar and gas becomes competitive.

The incentives to gas and the biomass limit were found not to have much effect on the shape of the CO₂ MAC, as opposed to the ban on nuclear and the ban on conventional coal. When nuclear is allowed, the MAC curve increases steeply because cheap abatement switching coal to gas in the electricity sector is not available, as can be seen comparing the MAC curves of the policy and nuclear scenarios. On the other hand, of course, the need to abate is less. If conventional coal is allowed the MAC curve will grow very slowly as cheap abatement is available mainly by reducing activity of very polluting coal power plants.

Besides looking at MAC for the different policy scenarios, it is also interesting to assess differences in total system costs for the modelled period (2000 to 2030) (Figure 3.6). The system costs increase with the severity of the emission cap and policy constraints. The costs for satisfying the demand for energy services from 2000 to 2030 decrease 10-13% if no policy assumptions are forced. The difference in total costs compared to the policy scenario is less 76 to 101 B€ which is roughly the equivalent to 2.01 to 2.65% of the 2005 GDP, respectively for CO₂ caps of +10% and -60%. This should not be read as GDP loss – it is simply a metric for comparison of values. Lifting the ban on nuclear is just marginally less expensive than the policy scenario: the difference between scenarios represents at most 0.01% of the GDP, whereas the incentives to gas and ban on conventional coal practically do not affect the total system costs.”

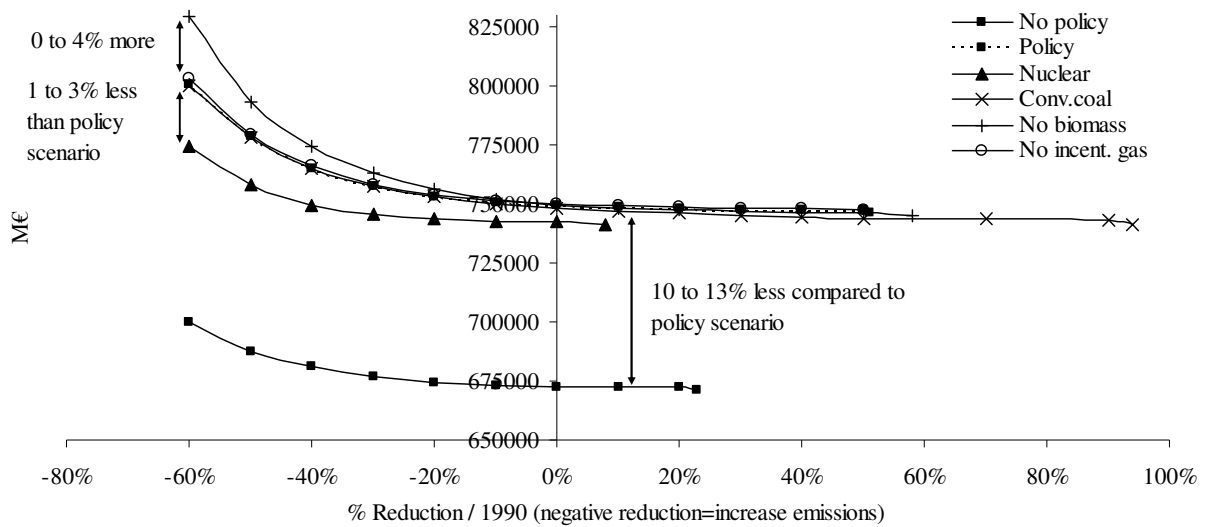


Figure 3.6. Total system costs for the 2000-2030 period (M€). The % values are the CO₂ emission caps compared to 1990 emissions (positive = increase in emissions).

Although the nuclear policy and conventional coal bans, the limit to biomass and the incentives to gas do not drastically affect total system costs, their significance is still important for national mitigation strategies. According to Figures 3.3 and 3.5, for expected carbon prices of European Union Allowances of 23€/t CO₂ in 2020 (Point Carbon, 2007), Portugal should reduce internally up to 8 Mt in 2020 in the policy scenario, compared to its own no cap emissions. This roughly represents an increase of 35% of 1990 levels. With the combination of unlimited nuclear, conventional coal and no incentives to gas, up to 15 Mt (-10% of 1990 levels) could be reduced internally at 23€/t CO₂ (Figures 3.3 and 3.5).

Nonetheless, 8 Mt abatement to get to +35% in emissions is still a large cheap reduction potential, especially when considering that if no additional measures are adopted to curb Portuguese CO₂ emissions, a growth of 77-64% is expected in 2020 (IA, 2006a). The MAC curve for the policy scenario shows that this trend can be altered at low cost.

Finally, it should be recalled that the Portuguese MAC curve does not consider: i) energy instruments that lower the carbon abatement marginal

cost³⁰, as is the case of the renewable electricity feed-in tariffs and CO₂ emissions trading, nor ii) structural changes in the economy. The MAC curves here presented reflect the continued global growth of the current energy intensive industry and no drastic changes in consumer preferences. In the next sections are outlined the fuel and technology changes that can lead to CO₂ abatement in the different policy scenarios.

3.4.2 Primary and final energy demand for the +10%, 0% and -30% CO₂ emission caps

In all modelled scenarios there is a global growth in the demand from 2000 to 2030, despite some response to the increase in energy prices. Because TIMES_PT is an optimisation model, energy efficiency measures are implemented in all scenarios and the primary energy consumption grows less than the demand. However, higher CO₂ emission restrictions result in smaller growth of energy consumption, except for uranium. In the +10% cap the primary energy consumption (excluding uranium) grows 10-22% from 2000 to 2020, whereas in the 0% and -10% caps the increase is of 8-19% and 4-11%, respectively.

The most evident fuel shift is the use of uranium replacing oil and gas in electricity generation, except when the assumed policies state otherwise. Nonetheless, oil continues to represent 31-58% of the overall primary energy supply. The relative importance of renewable and gas increases only if there is no nuclear. Coal's share is reduced in all scenarios from 18% in 2000 to 1-12% in 2020. This shift is also clear for final energy consumption. Coal disappears in all scenarios and the relative importance of oil products decreases, although it continues to be the most important final energy resource. Electricity's share increases from 20% in 2000 up to 37% in 2020 (28% for scenarios without nuclear). The gas share in the overall final energy demand increases in all scenarios from 5% in 2000 up to 16% in 2020. The renewables share increases in all scenarios from 10% in 2000 up to 22%, with

³⁰ This paper focuses on MAC and only briefly addresses total system costs. However, it should be mentioned that although feed-in-tariffs can lower MAC they usually contribute to higher total system costs since the costs of subsidising renewable technologies are passed to consumers via the electricity tariff.

the exception of the no biomass scenario (renewables are 6-8% of final energy use in 2020). In this scenario, because large quantities of biomass are not available, no biofuels are used in the transport sector and solar and gas replace biomass respectively in the residential and industry sectors.

The fuel switch does not correspond to a shift in the relative importance of economic sectors in the overall final energy demand. In 2020, in all policy scenarios and caps the transport sector continues to be the biggest energy consumer (37-41% of total final energy consumption), followed by industry (25-28%) (Figure 3.7). The commercial sector has the biggest increase in final energy consumption compared with 2000, up to 85% (75-44% increase in the policy scenario), followed by the residential and transport sectors (respectively 25-7% and 15-7% increase in the policy scenario). Finally, the differences in final energy demand in the six scenarios are higher for -30% cap than for the other two studied caps. This is mainly due to demand reductions in response to the increase in prices. For the +10% and 0% caps these demand reductions are smaller or inexistent since the cap can be met mainly by using alternative technologies. As the stringency of the cap increases alternative technologies are no longer enough and demand response plays a more important role in compliance. For more stringent emission caps the differences in energy prices across policy scenarios increase and so do demand responses.

3.4.3 Sector abatement for the +10%, 0% and -30% CO₂ emission caps

The fuel shifts mentioned in the previous section are motivated both by cost reduction and emission caps. Figure 3.8 depicts emission reductions for 2020 compared with emissions for each policy scenario without an emission cap. It should be noted that the sector mitigation in each scenario is different because unabated emissions in each policy scenario are different to start with, as mentioned in the previous section. In the scenarios without nuclear power, clearly electricity generation has the highest cost-effective reductions; it bears 45-74% of the total CO₂ abatement, especially in the conventional coal and no incentives to gas scenarios. The reductions are due to the

substitution of coal by wind and by new hydro power plants³¹. The relative importance of the abatement made by electricity sector decreases slightly as stringency of emission caps increase, but even for the more restrictive emission caps industry & CHP are always second in overall CO₂ abatement.

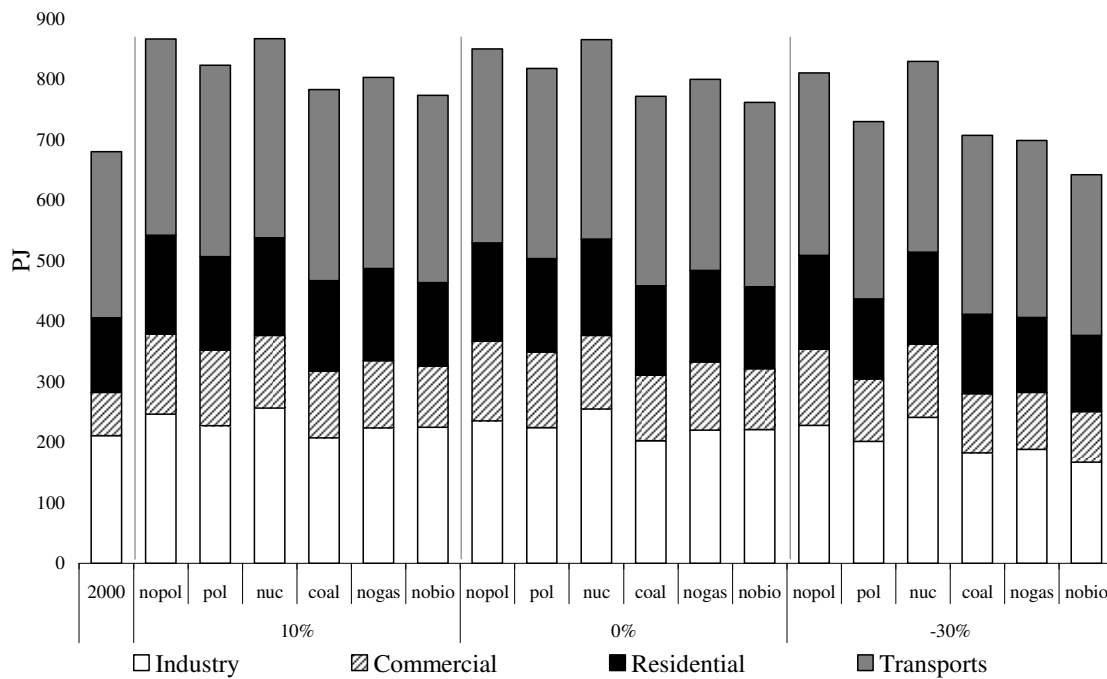


Figure 3.7. Final energy demand per sector in 2020 for the six policy scenarios: nopol - no policy; pol – policy; nuc – nuclear; coal – conventional coal; nogas – no incentives to gas; nobio – no biomass.

³¹ It should be noted that the evolution of electricity imports and exports is handled in a simplified way, as mentioned in section 3.2.4, by having set maximum limits on imports and exports for 2020. The resulting net electricity imports in 2020 range from -20 to +26 PJ which represent 5 to 17% of total electricity generated and 6 to 17% of CO₂ emissions of the electricity sector (in average 8% of the sectors' emissions). The bias introduced in the results is relevant, although not sufficient to invalidate its usefulness, since the main objective is to understand the dynamics between the different policy scenarios, all of which have the same assumptions regarding electricity trade.

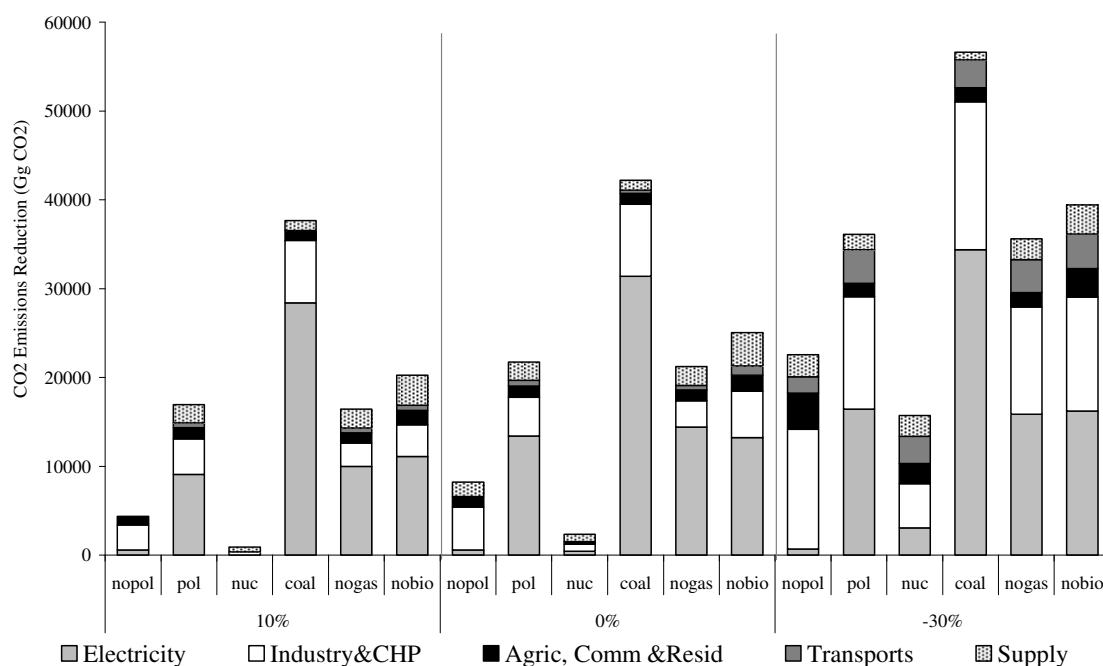


Figure 3.8. CO₂ emission reductions per sector for the six policy scenarios: nopol – no policy; pol – policy; nuc – nuclear; coal – conventional coal; nogas – no incentives to gas; nobio – no biomass. The emission reductions are estimated comparing with the emissions obtained without any CO₂ emission cap

In the scenarios without nuclear, industry & CHP are responsible for 14-35% of total abatement. Abatement in industry in the different policy scenarios is mainly due to: more efficient clinker and ceramic kilns and cement mills, more efficient ammonia production technologies, increased use of CCS, CHP and of green electricity and renewables for process heat in all industry sub-sectors.

With the exception of the conventional coal and no biomass scenarios, the primary energy supply sector also plays an important role in abatement due to the reduction of coal gasification plants (5-17% of total abatement).

The aggregated contribution for overall emissions reductions of the residential, commercial and agriculture sectors is always below 8% in the scenarios without nuclear. The commercial sector reduces its emissions in -4% from 1990 to 2020 only in the policy scenario, and it can increase

emissions up to 14-132% of 1990 emissions. Likewise, the residential sector increases emissions 60-165% from 1990. In these two sectors the main technological changes are the almost complete substitution of space heating, water heating and cooling technologies for more efficient and renewable based ones, as a choice for the most cost-effective increases in energy efficiency are - not fully realistically - assumed. In the -30% cap for the scenarios without nuclear 26% and 56% of the water heating is solar based, respectively for the commercial and residential sectors. Heat pumps provide up 47-53% of the heating needed, respectively for the commercial and residential. While the penetration of solar water heating is similar in the scenarios without nuclear, the penetration of heat pumps is higher if conventional coal is allowed, if there are no incentives to gas and especially with the limit on biomass (up to 69% and 67% of heat provided by heat pumps in the commercial and residential).

The transport sector does not play an important role in emission reduction in any scenario. In fact its emissions increase 87-135% from 1990 values. It contributes to 6-11% of the total reduction in the more restrictive cap (-30%) in the scenarios without nuclear. For the other two caps reductions are low (below 4% of total abatement) or none at all. The abatement in the transport sector is mostly due to introduction of using more efficient passenger vehicles and of buses and cars using biofuels: bio ethanol, biodiesel and DME produced from black liquors. The road freight transport sub-sector abates much less than passenger cars. In the no policy and no biomass scenarios abatement is achieved similarly but with less use of biofuels, particularly biodiesel, which is only competitive due to the policy assumption that forced its implementation in 2010. Nonetheless, the contribution of the transport sector for total abatement is the same 10% in the no biomass and in the policy scenarios, where biofuels are used.

3.4.4 Sensitivity analysis

A sensitivity analysis was carried out to the following model's critical parameters: i) hydro power availability factor; ii) costs of CO₂ storage and iii) discount rate. This analysis does not include emission reduction targets, since the main objective is to assess model response to the three studied parameters, and emission caps would bias the results. The results are shown in Table 3.6.

Table 3.6. Values of analysed parameters and respective model results in 2020 for the base case and the sensitivity analysis.

		Base value ^a	Hydro availability		Costs of CO ₂ storage		Discount rate	
			Value	% change	Value	% change	Value	% change
Hydro availability	n.a.	^b	n.a. ^b	-10 to +10	—	—	—	—
Costs of CO₂ storage	€/tC O ₂	8.3	—	—	5.8-11.3	-30 to +36	—	—
Discount rate	%	4	—	—	—	—	2-6	-50 to +50
Model results								
Hydro power	PJ	40.24	37-41	-6.9 to +0.9	40	0.0	57-40	+41.8 to 0.0
Stored CO₂	Gg	5000	5000	0.0	5000	0.0	2300-5000	-54.0 to 0.0
Total system costs^c	B€	750.96	751.42 - 750.90	+0.1 to 0.0	750.91 - 751.05	0.0	925.20 - 629.74	+23.2 to -16.1
Final energy	PJ	1016	1016	0.0	1010-1022	-0.6 to +0.6	1010-1022	-0.6 to +0.6
CO₂ emissions	Gg	72655	72917-72622	+0.2 to +0.1	72654	0.0	68754-72729	+1.9 to -1.9

^a For the policy scenario, without any CO₂ emission cap. Even without an emission cap, CCS still occurs because coal is much cheaper than gas and investment in coal without CCS is not allowed (see section 3.3). ^b Because there are eight different availability factors (AF) considered in TIMES_PT they are not all shown here; the two model runs were made for a variation of +10% and -10% for each of these AF. ^c The system costs are discounted and estimated by the model for the total period: 2000 to 2030.

The discount rate is the most sensitive of the studied parameters. Changes of 50% in the discount rate lead to large variations of generated hydro power and total system costs, but not of CO₂ emissions and final energy consumption, which vary less than 2%. On the other hand, total system costs, generated hydro power and quantities of stored CO₂ vary significantly with a reduction of the discount rate (more than 20%). The lowest discount rate hampers the penetration of less capital intensive electricity generation technologies, mainly a new integrated gasification combined cycle (IGCC) coal power plant with CCS. This technology replaces new hydro power plants which are favoured in the low discount rate case. Hydro power plants have both higher life time and specific investment costs than IGCC coal power

plants; respectively 5850-3500 €/kW for hydro plants and 1370 €/kW for coal IGCC. Although the decrease in the discount rate leads to a significant difference in parameters, its increase from 4 to 6% practically has no effects, except for the reduction of 16% in total system costs, which is simply the result of higher payment on invested capital.

For the other parameters – hydro availability and costs of CO₂ storage – there are no significant variations (less than 7%). In the particular case of CO₂ storage, it seems clear that the storage costs are not influencing the selection of coal CCS technologies. Coal is so much cheaper than gas³² that even without any emission cap coal CCS plants are implemented because no-CCS coal plants are banned as mentioned in section 3.3. Although the investment and operation and maintenance costs for no-CCS gas plants are lower than for coal-CCS plants, the cheaper fuel costs make coal CCS plants competitive even when there is no need to abate emissions. This indicated that the critical parameter for CO₂ storage is not storage costs but storage capacity, which is used to its limit in almost all sensitivity analysis.

Therefore, the variations in the model results are relatively small when compared to the large variations of the three critical parameters, which seems to point to the robustness of the TIMES_PT model.

3.5 Conclusions

This paper presents CO₂ MAC curves for the year of 2020 for different policy scenarios of the Portuguese energy system. Six policy scenarios were studied with different implementation of the energy policies currently in place. The reference policy scenario considers the following policies: a ban on nuclear power; a ban on new coal power plants without carbon sequestration and storage (hereafter named as conventional coal); incentives to natural gas

³² In the no policy scenario in 2020 coal for electricity generation costs approximately 1.78 €/GJ, whereas natural gas costs 5.96 €/GJ. When incentives to gas are considered, the gas price increases to 7.50 €/GJ. This large difference is due to the fact that most of the coal consumed in Portugal for electricity generation is delivered to the power plants at a very cheap cost, since they are located in close proximity to an international harbour. The gas, however, has to be delivered by pipeline, with much higher costs

power plants, and a cap on biomass use. Besides the policy scenario, the following alternative scenarios were studied: no policy, without any of the above mentioned policies; nuclear (policy scenario but allowing nuclear); conventional coal (policy scenario allowing conventional coal); no incentives to gas (policy scenario without incentives to gas); and no biomass (policy scenario with a limit on available biomass). The objective is twofold: to present the Portuguese marginal abatement costs curve for CO₂ emissions, and to quantify the impact of the present policies on the MAC curve.

It was found that the introduction of assumed policies significantly increases MAC: the policy scenario has 91 to 42% higher CO₂ MAC than the no policy scenario. The removal of the assumed policies leads to a significant decrease in total system costs of 10-13% (76-101 B€), roughly the equivalent to 2.01 to 2.65% of the 2005 GDP.

The marginal abatement costs difference in policy scenarios is essentially due to the ban on nuclear power, which is by far the most significant policy affecting MAC. In fact, the MAC of the nuclear scenario are closer to the no policy scenario than to the policy scenario (87-29% lower than the policy scenario MAC), as opposed to the other scenarios whose MAC are less than 20% different of the policy scenario. The limit on biomass also plays a significant role increasing MAC but only for “aggressive” emission caps representing an emission reduction from 1990 levels. For more moderate emission caps biomass is not playing an important role, as cost-effective abatement is done mainly in the electricity sector, without using biomass. Thus, for Portugal the use of biofuels in transport aiming to reduce CO₂ emissions is only cost-effective for reductions of 0% 1990 levels and beyond. The ban on new conventional coal power plants only has significant effects for “moderate” emission caps above +30% and for the 0% cap. The ban mostly reduces MAC as cheap abatement switching off polluting coals power plants is not available. The incentives to gas were found not to have a significant effect in MAC.

With exception of the incentives to gas and biomass limit, the studied policies alter the slope of MAC curves. The MAC curves of the scenarios without nuclear grow slower, due to cheap abatement switching from coal to gas in the electricity sector. The same happens if conventional coal is allowed because cheap abatement is available by reducing the activity of highly polluting coal power plants.

The policy scenario MAC curve shows a large cheap CO₂ abatement (below 23 €/tCO₂) potential up to 8 Mt in 2020. This corresponds to an increase of emissions of +35% of 1990 levels. Higher emission reductions imply marginal costs above 33 €/tCO₂ and to maintain 2020 emissions to 1990 levels a cost of 42 €/t has to be dealt with.

Cheap abatement options are provided by electricity generation, CHP and industry. The other sectors have less cost-effective options, such as the transport sector, or their share in total emissions is small, as in the commercial sector. One of the first measures adopted in the policy scenario is the increase of electricity generated from renewable resources from 31% in 2000 to 42-73% in 2020, depending on the emission cap and policy scenario. Thus, it is no surprise that the policy measures that condition the electricity generation sector have the most influence in MAC curve. Regarding the portfolio of renewable electricity technologies, hydro power seems to be the most competitive option. Electricity generated from hydro increases compared to the no cap case already for MAC of approximately 6 €/t CO₂ in the scenarios without nuclear. Wind is the second best option when MAC are around 30-40 €/t CO₂. Solar (either PV or thermal), geothermal or biomass are not competitive even for MAC higher than 100 €/t CO₂.

The results here presented should be handled with some caution due to a series of limitations of the used methodology and of the modelling tool. As to the methodology, the quantification of effects of policies in MAC curves has to be regarded with some caution because some of the model results for the no policy and nuclear scenario are unrealistic. At least 8.5 GW of nuclear power will be installed in 2020, which is highly unlikely, due to energy security and environmental and risk concerns. Another improbable model result is the massive installation of no CCS coal gasification plants to generate DME and methanol. These plants have high environmental impacts, such as SO₂ emissions, which are not taken into account here. Moreover these plants can have CCS technologies which were not considered. Furthermore, in all scenarios an assumption is made regarding the evolution of electricity imports and exports. Nonetheless, the different policy scenarios allow understanding how current policies affect the MAC curves and assessing maximum alterations in curves and CO₂ emissions.

Another relevant model limitation is that major alterations in the value added structure due to increases in fuel prices are not dealt with in TIMES_PT.

Furthermore, the demand for energy and materials is exogenous and only responds to the implemented policy constraints to the extent of the considered demand price elasticities. The demand reduction will influence macro-economic growth and constant gross value added structure of the GDP but this cannot be assessed with a partial-equilibrium model such as TIMES_PT. For example, the model does not show any increase in energy demand of the agriculture and chemical sectors due to increased use of biofuels requiring more fertilisers. This could partially be dealt with by adding such emissions in the emission factors of biofuels, but the feasibility of this option would be limited, as this would be a life-cycle approach mixed with an (quasi-)dynamic approach. Other limitations are the uncertainties in model inputs, especially the assumed potential for CO₂ storage, for sinks, and also some of the national primary energy potentials.

Further interesting model developments would include the consideration of micro generation technologies and of acidifying and particles emissions which significantly interact with CO₂ restrictions.

The most general conclusion is that even the limited set of policies in the energy domain assumed operant in this model exercise has a significant effect on the cost of CO₂ reduction. This interaction of policies therefore seems to be a prime subject for further analysis on cost-effective policy development in the energy and environmental policy domain, not only in Portugal.

3.6 Appendix – Other Exogenous information inputs included in TIMES_PT

The *energy supply and demand technologies for the base-year (2000)* were characterised considering the energy consumption data from EUROSTAT and the official DGGE national energy balance to set sector specific energy balances to which technologies profile must comply. Information on installed capacity, efficiency, availability factor, and input/output ratio were introduced using diverse national sources (IA, 2006a; CELPA, 2003; DGGE, 2005; EDP, 2002; EDM, 2005; ERSE, 2001; ERSE, 2006; IGM, 2000; INETI, 2003; INE, 2000b; LIPOR, 2005; REN, 2005; REN, 2006; SEIA, 2000; PEGOP, 2005; Turbogás, 2005; Valorsul, 2005). This was followed by a bottom-up approach that adjusted the technologies specifications to achieve coherence with official energy statistics. This bottom-up approach

was very relevant for the residential and commercial sectors, for which there is less detailed information on existing technologies.

The energy supply and demand *technologies beyond the base year* are compiled in an extensive database with detailed technical and economic characteristics of new energy technologies. This was developed within the NEEDS project and validated with Portuguese stakeholders for industry, electricity generation, and solar technologies.

The costs data on *carbon capture and storage* considered in TIMES_PT refers to the costs of carbon capture and compression and are embedded in the several supply and demand energy technologies in TIMES_PT, using cost data from IPCC (2005) and Hendriks et al. (2004). Only one CO₂ transport technology and one storage technology are included in the model. The following CO₂ storage costs were considered: transportation costs of 3 €/t CO₂, storage costs of 0.3 €/t CO₂ for pumping the gas underground, and cost of investment in the underground storage facility of 5 €/t CO₂ (Hendriks et al., 2004).

TIMES_PT modelling of end-use of energy services and material requires to *breakout fuel consumption by end-use* (e.g. clothes washing, process heat). Several data sources were used: data from CIEMAT³³, within the NEEDS project (REE, 1998; MITYC, 2003); National Inventory Report on GHG (IA, 2006); national studies on renewables (Gonçalves, *et al.*, 2002a e 2002b) and on electricity end-use (Júlio, S. et al., 1997; DGGE/IP-3E, 2004); and the PNAC energy demand scenarios. For the residential sector the *load diagram* data developed by ADENE the National Energy Agency was used (Enertech *et al.*, 2002). The Spanish load diagram data (REE, 1998) was adopted for the commercial sector since there is no Portuguese specific data. Because it was not possible to breakout the energy demand according to the load diagram for industry and transport due to the lack of information, the model does not consider seasonal or daily demand variations for these sectors.

A long-term *price elasticity of demand* of -0.3 is used for the following demands: (1) Industrial products; (2) Energy use in other industrial sectors,

³³ CIEMAT- Centro De Investigaciones Energéticas, Medioambientales y Tecnológicas of the Spanish Ministry of Education and Science.

transport and agriculture; (3) Energy end-uses in the residential and commercial sectors except cooking, which has a price elasticity of -0.2 and -0.1, respectively for the commercial and residential sectors. The elasticity values are generic for EU countries and were supplied by Leuven University.

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