MARGINAL CO_2 ABATEMENT COSTS FOR THE PORTUGUESE ENERGY SYSTEM – SCENARIOS ANALYSIS FOR 2030

J. Cleto, S. Simões, P. Fortes and J. Seixas
Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa, DCEA - Campus da Caparica, 2829-516 Caparica, Portugal

Abstract This paper presents the marginal abatement costs (MAC) curves for CO_2 emissions for 2020 and 2030, estimated for the Portuguese energy system using the TIMES_PT model. The MAC curves were derived from a set of scenarios for the period 2000 to 2030, assuming the absence of policy instruments, such as the renewable electricity feed-in tariffs. For each scenario, TIMES_PT finds the combination of energy technologies to satisfy the demand for energy services at the minimum system cost. The MAC curves show a large CO_2 abatement potential up to approximately 40 000Gg in 2020 at a marginal cost less than 25 €/tCO_2. This corresponds to the maintenance of CO_2 emissions to +20% of 1990 levels. To maintain the 2020 emissions to 1990 levels, a marginal cost of 69 €/t has to be dealt with. TIMES_PT model finds the supply and demand technologies to fulfill energy demand and to ensure compliance with CO_2 emission limits. Thus, the results also allow the identification of the most cost-effective emissions reduction for each economic sector, namely the electricity generation sector and industry.

Keywords Energy scenarios, CO_2 abatement marginal cost, optimization modeling, Portugal

INTRODUCTION

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. However, the Portuguese GHG emissions have been increasing sharply and the country is far from its goal. According to the last national forecasts, and without additional climate mitigation policies, the emissions for the year 2010 will be 45-48% above 1990 levels (IA, 2006a). This is mainly due to the continuous increase, both of the energy demand and of the GDP energy intensity. Projections point to a growth rate of 70% for primary energy demand from 1990 to 2010, whereas the GDP is expected to grow only 49% (IA, 2006a).

The Portuguese energy supply is highly dependant on imported energy, mostly oil. In 2005 about 85% (DGGE, 2007) of the national energy demand was met by imported fossil fuels (oil, coal, and natural gas).

Electricity generation, transport and industry bear the lion share of the national energy demand (respectively with 32%, 30% and 18% of total energy demand in 2005), but whereas there is high awareness for reducing the energy intensity of Portuguese industry, the demand of the transport sector has grown dramatically (91%) between 1990 and 2005. Aware of this, the national energy policy is based on three strategic goals: energy security, sustainable development and national competitiveness.

Although national energy and GHG emission scenarios have been developed to assist in achieving the Kyoto commitments, the national marginal abatement cost (MAC) curve for GHG or CO_2 emissions has not been estimated. The knowledge of the marginal cost of reducing an additional unit of CO_2 is fundamental to define the emissions reduction potential, and thus to support the definition of GHG control policies. The objective of this paper is to present the marginal abatement costs curve for CO_2 emissions for the Portuguese energy system for the years 2020 and 2030, derived by an optimization model, TIMES_PT.

TIMES_PT MODEL

TIMES_PT[1] is a linear optimisation bottom-up technology model generated with TIMES[2] model generator. TIMES was developed by ETSAP[3] 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. Examples of policies that can be evaluated include building codes, energy or emission taxes, investment subsidies, emission intensity standards, and regulations.

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

---

[1] The implementation of the TIMES model for Portugal has been undertaken within the international 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.

[2] 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.

[3] Energy Technology Systems Analysis Programme

energy supply and energy trade, according to the following equation (Loulou *et al*, 2005):

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

NPV: net present value of the total costs
ANNCOST: Total annual cost
d: general discount rate
r: region
REFYR: reference year for discounting
YEARS: set of years for which there are costs[4]

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 VAT and the ISP, the tax on oil products which are differentiated by energy carrier. The revenues usually considered within TIMES models include subsidies, recuperation of sunk material and salvage value. However, these are not included in TIMES_PT. More information on TIMES development and functioning can be found in Loulou *at al* (2005).

TIMES_PT Model structure

TIMES_PT represents the Portuguese energy system from 2000 to 2030. The following sectors are modeled: primary energy supply; electricity generation; industry; residential; commercial; agriculture, and transport. In order to ensure a close approximation to real energy, materials and monetary flows, energy demand and supply technologies are modeled in detail, including mass balances. The model structure for the Portuguese system, presented in Figure 1, was adjusted from the model structure developed under the NEEDS[5] project.

[4] 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.

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

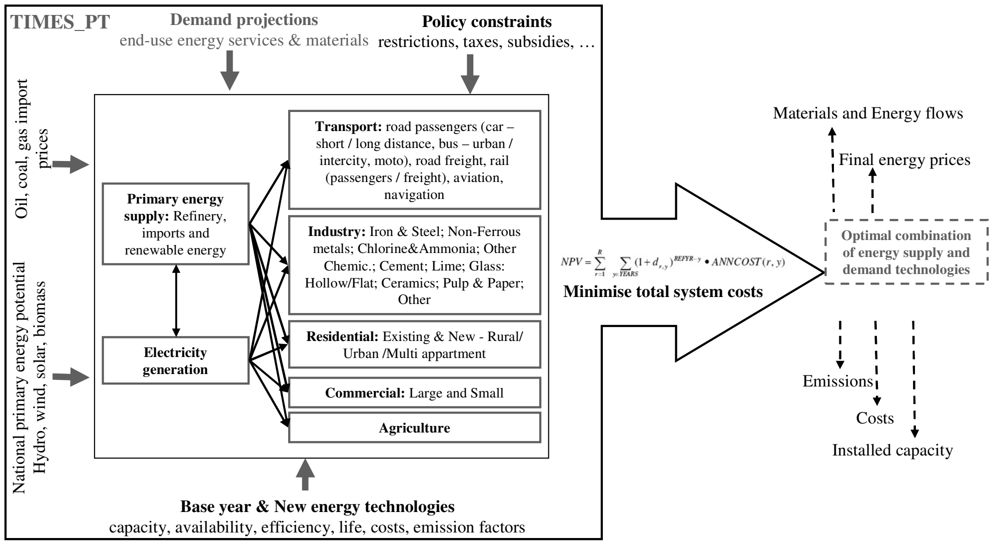

Figure 1. Structure of the TIMES_PT model

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 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 not an economic model and thus does not consider 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.

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-E3[6] 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 the following equation (adapted from van Regemorter and Kanudia, 2006),

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

DEM – Final demand (materials or end-use energy)
DGDR - Macroeconomic drivers
ELASI and ELASP– income and price elasticity of final demand to DGDR provided by Leuven University[7]
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 2 illustrates the approach to deal with the residential sector demand for energy end uses, following the NEEDS framework. 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. Data from 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 National Institute for Engineering and Industrial Technology (Aguiar *et al.*, 2002) were the main data sources.

---

[6] GEM-E3: General Equilibrium Model for Energy-Economy-Environment: http://www.gem-e3.net/

[7] 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

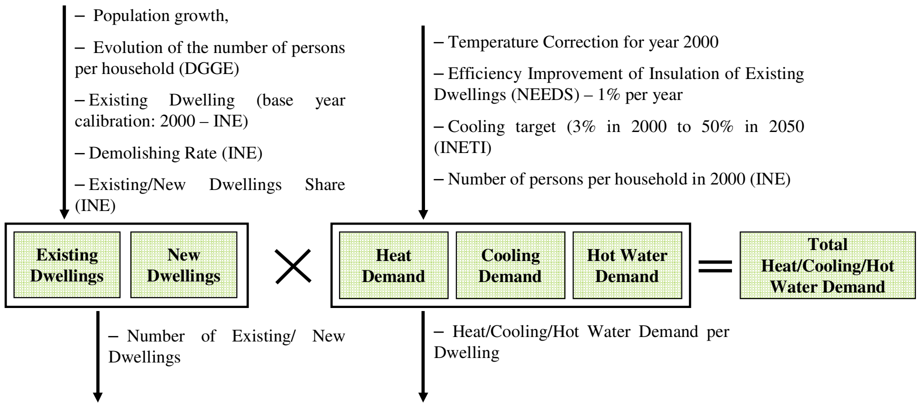

Figure 2. Projection of the demand in the residential sector for hot water, heating and cooling

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 sector for which the GEM-E3 generated projection was replaced 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 Figure 3.

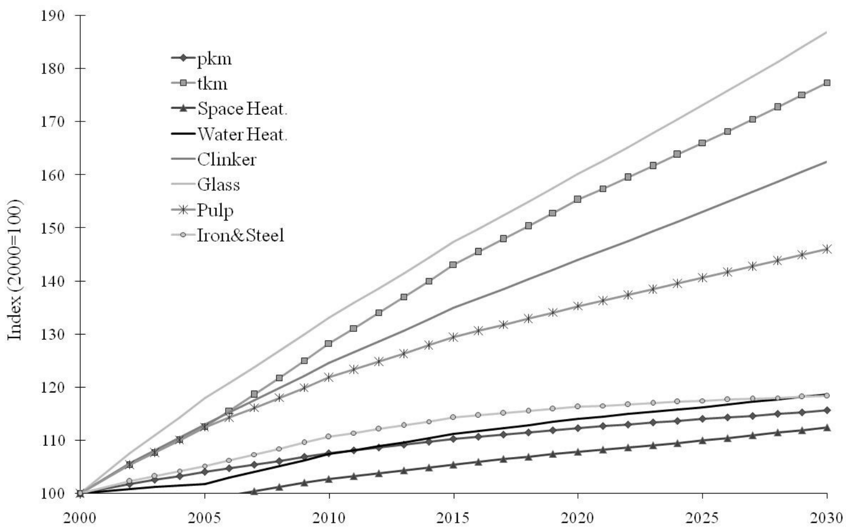

Figure 3. Evolution of the demand for some of the end-use energy services and materials considered in TIMES_PT

Other exogenous information inputs

The *energy supply and demand technologies for the base-year (2000)* were characterised in a two-step approach. Firstly, a top-down approach uses the energy consumption data from EUROSTAT and the DGGE national energy balance to set sector specific energy balances to which technologies profile must comply. Information on installed capacity, efficiency, availability factor, input/output ratio were introduced using diverse national sources, from energy and industry companies and several studies (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). Secondly, the bottom-up approach adjusts the technologies specifications to achieve coherence with official energy statistics. This bottom-up approach was 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 selected by TIMES_PT from an extensive database with detailed characteristics of new energy demand and supply technologies, developed within the NEEDS project. This technology database was validated with Portuguese stakeholders for industry, electricity generation, and solar technologies. Adjustments were made in several variables, e.g. availability factors, date of market entrance and investment costs. Some additional technologies were added in order to fine tune the database with the Portuguese energy system.

Carbon storage and sequestration is considered in TIMES_PT in a simplified way, due to the lack of information on the potential for Portugal. For the moment is assumed that 5000 Gg CO_2/year storage potential is available from 2015 onwards. This corresponds roughly to 7-6% of the emissions included in TIMES_PT, respectively for 2010 and 2020, according to PNAC (IA, 2006a). This potential has a great uncertainty which was dealt with via a sensitivity analysis, described in the Discussion. The costs of carbon sequestration are embedded in the several supply and demand energy technologies in TIMES_PT. However, the model considers one generic CO_2 transport technology and one generic storage technology. The CO_2 transportation costs are of 3 €/t, whereas the storage costs are of 0.3 €/t for pumping the gas underground. The investment costs for the underground storage facility are of approximately 5 €/t.

TIMES_PT modeling of end-use of energy services and material requires to *breakout fuel consumption by end-use* (e.g. clothes washing, heating, machine drive, process heat). For this the following data sources were used: data from CIEMAT[8], within the NEEDS project (REE, 1998; MITYC, 2003); national emission inventories (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 from the EURECO project developed by ADENE (National Energy Agency) was used (Enertech *et al.*, 2002). Spanish data (REE, 1998) was adopted for the commercial sector since there is no national data. It was not possible to breakout the energy demand according to the load diagram for industry and transport due to the lack of information. Thus, for these sectors the model considers no seasonal and daily variations of the demand.

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 1). It should be stressed that there is a large uncertainty due to the lack of data for some cases. Uncertainty was dealt with via a sensitivity analysis, described later.

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).

The model considers demand *price elasticity* for the different materials and energy end-uses. A price elasticity of -0.3 is used for the following demands: (1) Industrial products, such as cement, glass, steel, paper, ammonia and chlorine, among other; (2) Energy use in other industrial sectors, transport and agriculture; (3) Energy end-uses in the residential and commercial sectors, namely heating, cooling, water heating, lighting, refrigeration, cloth washing and dish washing. For cooking, the price elasticity is of -0.2 and -0.1, for the commercial and residential sectors. The elasticity values are generic for EU countries and were supplied by Leuven University. TIMES_PT uses a discount rate of 4%.

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

Table 1. National Primary Energy potentials considered in TIMES_PT

Primary Energy	**Used in 2000 →Potential in 2030 (% increase until 2030)**	**Reference**
Wood products (PJ)	71.7→**100** **(+28%)**	Best guess
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%)**	Best Guess 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%)**	Best Guess
Hydro (PJ)	40.2→**95** **(+58%)**	Pinho, M. (2007)
Wind off shore (GW)	0.0→**2** **(+100%)**	Best Guess
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- electricity generation (GW)	0.0→**2** **(+100%)**	Best Guess
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., Sarmento, A. (2004)

Policy assumptions

The model considers some constraints to reflect the most relevant energy policies in place until December 2005, although some are not explicitly modeled such as the subsidies to renewable energy. The base scenario, hereafter referred to as Kyoto scenario, takes into account the following policy assumptions:

1. A ban on nuclear power due to the political inacceptability of this option in the modelled time horizon;
2. A minimum of electricity generated from gas combined cycle from 2010-2030, following the energy sources diversification policy and support to use of natural gas. The generated electricity corresponds to at least 1100 MW installed capacity;
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 coal technologies 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;
6. Electricity generation from wood residues will continue throughout the lifetime of base-year plants following forest fire control policies;
7. A minimum of 1.1 MW 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;
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. From 2015 onwards at least 39% of generated electricity will be from renewable sources following the Directive 2001/77/EC;
10. From 2010 onwards the total CO_2 emissions can not exceed 63 344 $GgCO_2$, following the reasoning of the national commitment within the EU burden sharing agreement;
11. The value added tax (VAT) as well as the ISP tax, differentiated according to the energy carriers, were included, as presented in Table 2.

Table 2. Energy taxes considered in TIMES_PT

Energy carriers	2001		2005		2010-2030	
	ISP (€/PJ)	VAT (%)	ISP (€/PJ)	VAT (%)	ISP (€/PJ)	VAT (%)
Coal – RCA, supply & industry	0.00	17	0.15	21	0.16	21
Coal – electricity & CHP	0.00	17	0.00	21	0.00	21
Oil– residential & commercial	6.68	12[9]	2.48	12	3.73	12
Oil – electricity & CHP	0.00	12	0.00	12	0.00	12
Oil - agriculture	1.63	12	2.11	12	2.78	12
Oil - industry	0.69	17	0.38	21	0.38	21
Gas – RCA, supply & industry	0.20	5	0.00	5	0.00	5
Gas – electricity & CHP	0.00	5	0.00	5	0.00	5
Gas - transport	0.20	5	2.60	5	2.72	5
LPG – RCA & industry	0.16	17	1.58	21	0.69	21
LPG - transport	8.70	17	4.52	21	6.82	21
Diesel - agriculture	8.98	17	11.48	21	14.22	21
Diesel - transport	6.68	17	8.54	21	10.58	21
Gasoline - transport	11.46	17	18.04	21	20.57	21
Biofuels[10] - transport	8.98	17	11.48	21	14.22	21
Kerosene – transport	0.00	17	0.00	21	0.00	21
Heavy fuel oil - transport	0.00	12	0.00	12	0.00	12
Naphta - industry	0.00	17	0.00	21	0.00	21
Biomass – all sectors	0.00	17	0.00	21	0.00	21
Electricity – all sectors	0.00	5	0.00	5	0.00	5

Note: RCA states for Residential, Commercial and Agriculture.

Calibration and validation

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

1. To replicate real evolution of electricity imports and exports - affected by interconnection capacity - these have increasing maximum limits from 2000 to 2030, up to a maximum import and export of 60 and 30 PJ, respectively. 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 COGEN – National CHP Association

[9] It is assumed that oil consumption in the residential and commercial sectors is essentially for heating. Thus the VAT for heating is applied.

[10] Biodiesel, ethanol, methanol

expectations for the future. Thus, in 2001 32% of all electricity consumed in industry was from CHP. 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 and power;

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 in the residential and commercial sectors is delayed by inertia factors. These were defined for the penetration of efficient lighting and electric, biomass, LPG and diesel technologies for cooking, space heating, and water heating;
5. Based on information provided by GALP, the major Portuguese natural gas supplier, only 85% of the residential and commercial sector needs can be met with natural gas, due to geographic and technical limitations;
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.

The results of the base-year calibration are shown in Figure 4.

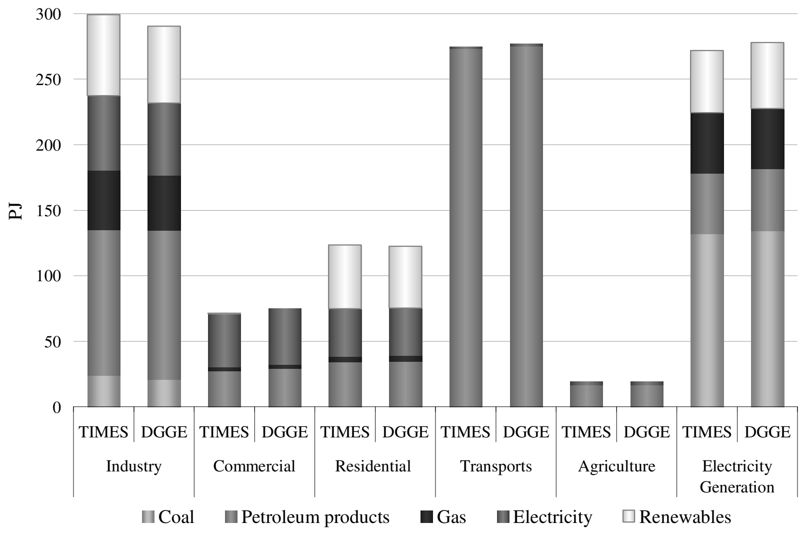

Figure 4. Comparison of the final energy consumption estimated by TIMES_PT for 2000 and the DGGE national energy balance

GREENHOUSE GAS ABATEMENT SCENARIOS

The TIMES_PT estimates CO_2, CH_4 and N_2O emissions from combustion and productive processes. Therefore, the following GHG emissions are not considered: from solvents use, non-combustion agricultural activities, waste management, fugitive emissions from fuels and f-gases. These GHG emissions sources account for approximately 20% of national emissions in 2010 (IA, 2006a). This paper, however, deals exclusively with CO_2 emissions.

The Kyoto scenario considers an emission restriction of CO_2 emissions from 2015 to 2030, following the Portuguese commitment under the Kyoto Protocol and the EU burden sharing agreement, which corresponds to an increase of 27% of 1990 emissions. The Portuguese assigned amount is 386 956.503 Gg CO_2e for the first commitment period (IA, 2006b), and thus, an annual average ceiling of 77 391 Gg CO_2e from 2015 onwards is considered for modelling purposes. TIMES_PT considers 80% of this national annual ceiling, and also 80% of the sinks capacity which amounts to 2 698.79 GgCO_2/year (IA, 2006a). It is assumed that this sink potential is kept constant until 2030, with a CO_2 removal cost of 5.5 €/t CO_2.

This adds up to an emission restriction of 63 344 GgCO_2e from 2015 onwards for the Kyoto scenario.

To derive the marginal abatement cost curves for CO_2 emissions for 2020 and 2030, a set of six scenarios for CO_2 emissions cap was built on top of the Kyoto scenario. The scenarios under study range from a maximum increase of 27% in 2020 compared to 1990 levels to a maximum decrease of 30%, with intermediate CO_2 caps, as presented in Table 3.

Table 3. CO_2 emission restriction scenarios modelled in TIMES_PT

Scenario (% compared to 1990 emissions)	**Emission restriction (Gg CO_2)**	
	2015	**2020**
Kyoto	63 344	62096
+20%	63 344	57563
+10%	63 344	52766
0%	63 344	47969
-10%	63 344	43172
-20%	63 344	38375
-30%	63 344	33578

As mentioned in the previous section, no policy instruments are considered in these emission scenarios, most notably CO_2 emission trading - neither the EU scheme nor the Kyoto protocol one, and the Kyoto mechanisms. This does not hinder the results since the main objective is to define the national internal CO_2 marginal abatement cost curve which will then be useful to assess the different external abatement possibilities.

RESULTS

Marginal abatement curve

The CO_2 MAC curves for 2020 and 2030 for Portugal obtained with TIMES_PT are presented in Figures 5 and 6. As expected, the MAC curve for 2020 is slightly higher, since abatement options are fewer when compared with the 2030 horizon. MAC curves increase sharply for emissions reductions above 41 000 Gg in 2020 and 50 000 Gg in 2030. Marginal abatement below these values costs up to 23 €/t CO_2 and 15 €/t, respectively for the 2020 and 2030. For higher reductions, marginal costs increase smoothly in the 2020 curve, whereas in the 2030 curve there is a second jump for reductions above 66 000 Gg CO_2. In this point, marginal costs rounds 69 €/t CO_2, and more than double for an increase in abated emissions of only 8%.

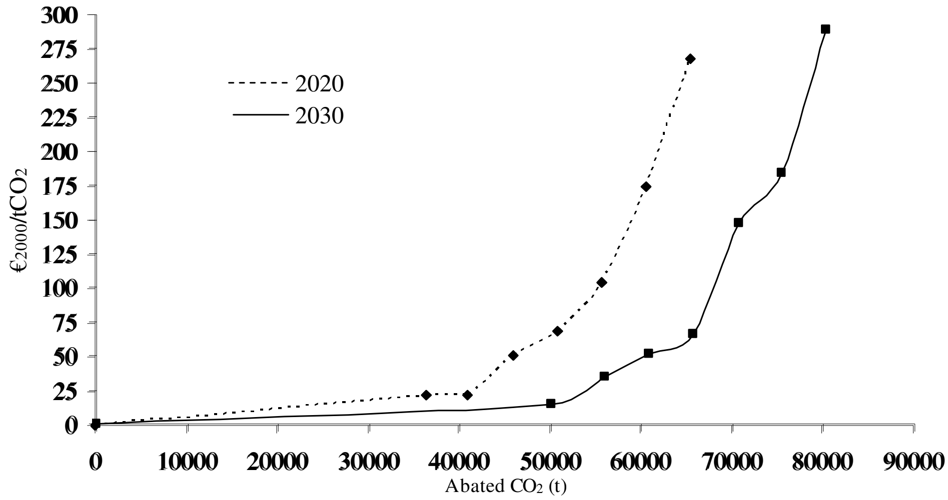

Figure 5. Marginal abatement costs curves for the Portuguese energy system

Considering expected carbon prices for European Union Allowances of 23€/t in 2020 (Point Carbon, 2007), Portugal should reduce internally up to 41000 Gg, which roughly represents an increase of 10% of 1990 levels.

For emission reductions below 1990 levels, the Portuguese energy system presents higher prices, starting from 66€/t and 69€/t, respectively for 2020 and 2030 (Figure 6).

From the present study, it appears that Portugal has a large cheap reduction potential: 40 to 55 thousand Gg can be abated with marginal costs below 25€/t both for 2020 and 2030. However, this does not stretch to reductions below 1990's emissions without significant changes in the economy. These MAC curves reflect the continued global growth of the current energy intensive industry and no drastic changes in consumer preferences.

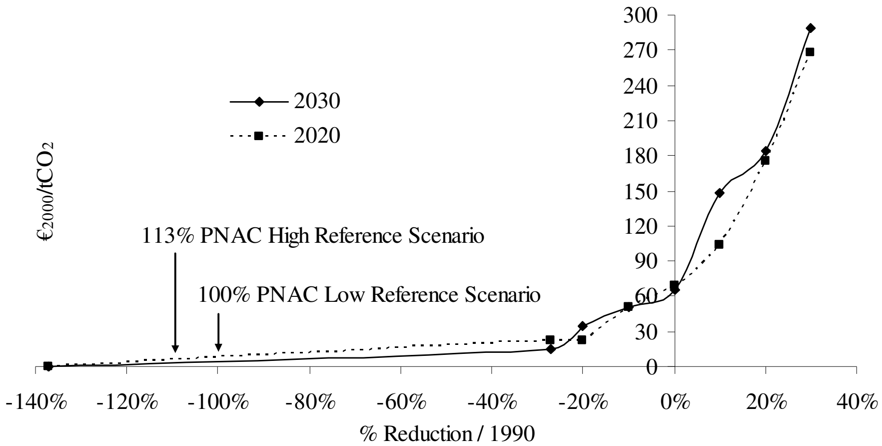

Figure 6. Marginal abatement costs for Portugal - % reduction from 1990 levels

The Portuguese CO_2 MAC curve for 2020 obtained with TIMES_PT was compared with French, Italian, UK and Germany curves obtained by the POLES model (Kitous, 2006). The marginal cost of 69 €/t CO_2 referred to 0% reduction from 1990 levels for Portugal compares with 80 €/t for France, 40€/t for Italy, and below 20€/t for Germany and the UK. Whereas emission reductions of 20% cost around 60€/t CO_2 for these two countries, Portugal presents costs of 184 €/t, which are closer to France and Italy. However, it should be underlined that the low cost reduction potential for these four countries is much smaller than for Portugal. Moreover, it should be recalled that the Portuguese case does not consider energy instruments that lower the carbon abatement marginal cost, as is the case of the renewable electricity feed–in tariffs and the CO_2 emissions trading.

If no additional measures were adopted to curb Portuguese CO_2 emissions, a growth of 113-110% was expected in 2020, compared to 1990 levels (IA, 2006a). The 2020 MAC curve clearly shows that this trend can be altered at low costs. The fuel and technology changes that can lead to this are discussed in the following sections.

Primary and final energy demand

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, stricter CO_2 emission restrictions result in smaller growth of energy consumption or even reductions. In the Kyoto scenario the primary energy consumption grows 11% from 2000 to 2020, whereas in the other scenarios only increases 8-1% or is reduced (-1 and -5%) for the two more strict scenarios. For 2030 there is a similar pattern with a 12% increase for Kyoto and variations +9 to -3% in the other scenarios.

Regarding fuel shifts, although oil continues to represent more than 45% of the overall primary energy demand in all scenarios, the relative importance of natural gas or renewable increases, depending on the scenario. Coal's share is reduced in all scenarios from 16% in 2000 to 9-1% in 2030. This shift is also patent for final energy consumption. Coal almost disappears in all scenarios and the relative importance of oil products decreases, closely followed by renewable. In fact, in the -30% scenario in 2030, renewable have a higher contribution than oil. Renewable's share increases from 12% in 2000 up to 31-36% in 2020-2030. Gas and electricity's shares in the overall final energy demand are similar in all scenarios ranging from 14-17% for gas and 15-19% for electricity. Thus gas consumption increases slightly more than electricity.

There is also a shift in the relative importance of economic sectors in the overall final energy demand. Whereas in 2000 transport and electricity generation are the biggest energy consumers, in 2030 they are overtaken by industry in most scenarios (Figure 7). Since the demand grows similarly for the three sectors, this indicates efficiency improvements in electricity generation and transports.

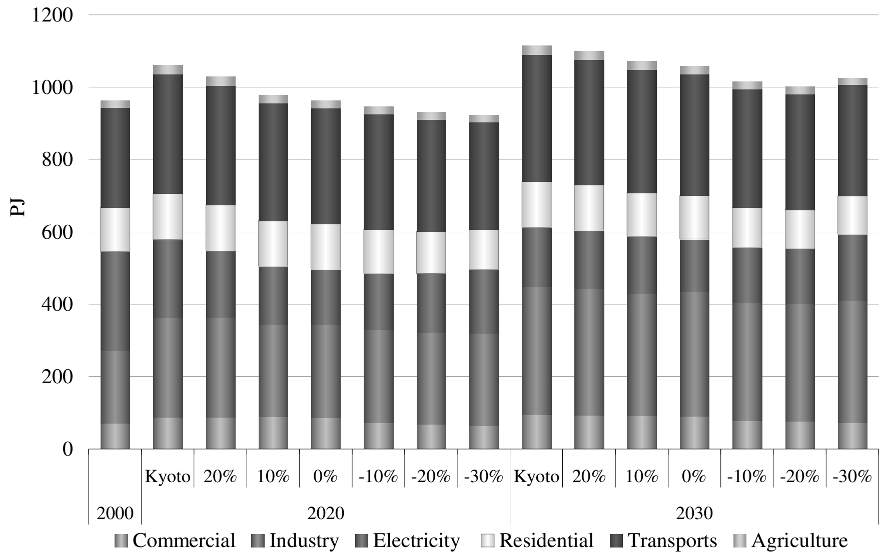

Figure 7. Final energy demand per sector

Sector abatement

The fuel shifts are motivated by cost reduction and the CO_2 emission ceilings. Clearly the electricity generation and industry have the highest cost-effective reductions in 2020 (Figure 8). In the +20% scenario 99% of CO_2 abatement is made by the electricity sector, due to the substitution of coal by wind. For the +10%, 0% and -10% scenarios the abatement burden is shared in almost equal parts by electricity generation, closely followed by industry. However, in the two more strict scenarios industry reduces more than electricity generation, mainly due to the following: more efficient cement mills, clinker and ceramic kilns, more efficient ammonia production technologies, increased use of CHP and of green electricity and renewables for process heat in all industry sub sectors.

The transport sector also plays an important role in emission reduction for the -20% and -30% scenarios, mostly due to the changes in the fleet of passenger cars that use of alternative fuels such as DME and ethanol. On the other hand the combined abatement of the residential, commercial and agriculture sectors is not higher than 5% of global abatement in 2020.

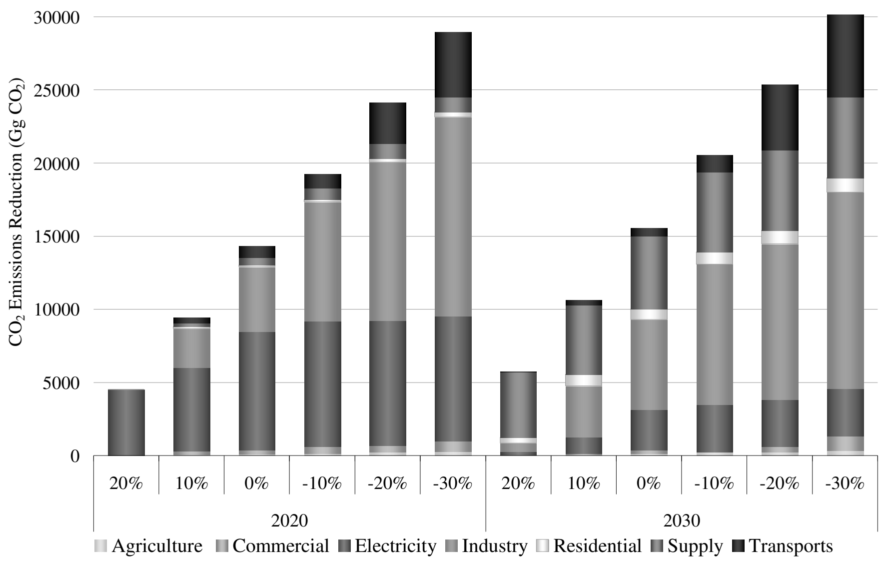

Figure 8. CO_2 emission reductions per sector

In 2030 the abatement burden is shared by industry and the primary energy supply sectors.). In the +20% scenario 78% of CO_2 abatement is made by the primary energy supply sector. The coal gasification technology to produce methanol for transports implemented in the Kyoto scenario is not implemented in any of the other scenarios, thus causing such a reduction in CO_2 emissions. For the +10% and 0% scenarios, the abatement of industry and primary energy supply are close, but the weight of industrial abatement (and transport) increases with the restrictions. Emission reduction in industry in 2030 is similar to 2020, with continued increase of CHP and replacement of equipments for more efficient ones. It should be noted the implementation of a technology with carbon storage and sequestration in clinker production, and use of hydrogen fuel cells in CHP. This hydrogen is generated from black liquors gasification in the -30% scenario.

The transport sector contributes to 18-19% reduction in the more restrictive scenarios (-20% and -30%) by using biofuels and more efficient passenger and freight vehicles. For the other scenarios reductions are low or none at al, as for the +20% scenario.

Once again the residential, commercial and agriculture sector have relatively low contribution for overall abatement. However, this is essentially because these sectors have low contribution for total emissions. The commercial sector reduces its emissions in 42-47% from 2000 to 2030. The residential sector increases emission in the three less restricted scenarios, but for the others achieves reductions from 4-9% from 2000 to 2030. These emission reductions have two causes: (1) reduction in the demand for energy services due to the increase in fuel prices due to the emission restriction, and (2) the complete substitution of space heating, water heating and cooling technologies for more efficient and renewable based ones. In the -30% scenario in 2030, 39% and 62% of the water heating is solar based, respectively for the commercial and residential sectors. Heat pumps provide 64-40% of the heating needed, respectively for the commercial and residential.

DISCUSSION

The CO_2 MAC curves for the Portuguese energy system show a large cheap CO_2 abatement potential up to approximately 40 000 Gg in 2020, corresponding to the maintenance of emissions to +20% of 1990 levels. Higher emission reductions imply marginal costs above 25 €/tCO_2, and to maintain 2020 emissions to 1990 levels a cost of 69 €/t has to be dealt with.

Most of the abatement is undertaken by the electricity generation and industry in 2020, and by industry and primary energy supply in 2030. The other sectors have less cost-effective options - transport sector – or their weight is small compared to total emissions - commercial sector. One of the first measures adopted by the model is the increase of electricity generated from renewable resources in all scenarios, from 32% in 2000 to 33-62% in 2020-2030. Hydro plays a fundamental role, and the model considers average hydrological conditions.

The results here presented should be handled with some caution due to a series of uncertainties. One of the most relevant is the fact that TIMES_PT assumes constant macro-economic growth and constant gross value added structure of the GDP until 2030. Thus, major alterations in the GDP structure due to increases in fuel prices are not dealt with. Other sources of uncertainty refer to the potential for CO_2 storage and sinks potential, and also to some of the national primary energy potentials.

Therefore, a sensitivity analysis was carried out to some of these critical parameters: hydro power availability factor (variations of -10% and +10%); costs of CO_2 storage (approximate variations of -20% and +20%) and discount rate (tested 2% and 6% discount rate against a default value of 4%). It was observed that changes in these parameters imply significant changes to the energy system: electricity generation from hydro varies from 16% to 40% of total electricity generated in 2030 for the availability factor variation of -10% and +10% respectively; changing the costs of CO_2 results in a utilization of 50% to 100% of storage potential; changing the discount rate by a factor of +50 or -50% introduces changes of +18 to -18% on the overall system cost. Such relatively small variations could make the discount rate to be perceived as a non critical parameter. However, it should be noted that the lowest discount rate delays the penetration of new technologies and stops the entrance of some of the most advanced technologies (e.g. a coal power plant with CO_2 sequestration).

A more systematic sensitivity analysis will be further elaborated including other parameters such as biomass potential, industrial CHP potential and minimum electricity share for satisfying some residential and commercial demands. Finally, further model developments include the consideration of micro generation technologies and acidifying and particles emissions which significantly interact with CO_2 restrictions. The next steps also include modelling feed-in-tariffs for renewable electricity and CHP, and the EU Emission Trading Scheme.

ACKNOWLEDGEMENTS

The authors acknowledge the Portuguese Science and Technology Foundation for funding the E2POL research project, and a PhD scholarship that supports the present work. The TIMES_PT model was implemented within the European Union research project *NEEDS – New Energy Externalities Developments for Sustainability*. The inputs of its research partners contributed significantly to the presented work.

NOMENCLATURE

DGGE – General Energy and Geology Directorate of the Ministry of Economy

IA – Portuguese Environment Agency

NEEDS- New Energy Externalities Developments for Sustainability

PNAC – National Climate Change Programme

REFERENCES

IA - Instituto do Ambiente. PNAC. [*National Climate Change Programme*]. *Programa Nacional para as Alterações Climáticas*. Instituto do Ambiente, Lisbon, 2006a.

DGGE. *National Energy Balance.* Directorate for Geology and Energy of the Ministry of Economy and Innovation. 2007. Available at: [www.dgge.pt]

Loulou, R., Remme, U., Kanudia, A., Lehtila, A. and Goldstein, G. *Documentation for the TIMES model - PART I.* Energy Technology Systems Analysis Programme, 2005. Available: [www.etsap.org/tools.htm]

Van Regemorter, D., Kanudia, A. *Projections of the demand of energy services for NEEDS*. Unpublished working paper from the NEEDS project. December 2006.

DGGE. *Estimates based on the "Survey on Energy Consumption in the Residential Sector"*. DGGE (1988, 1996). 1996. Unpublished.

INE. [*Building Construction Statistics - 2000*]. INE, 2000a. Lisbon. Available at www.ine.pt

INE. [*Building Construction Statistics - 2001*]. INE, 2001. Available at www.ine.pt

INE. [*XIV General Population Census - Main characteristics of private households and dwellings; Comfort parameters of families*]. *XIV Recenseamento Geral à População Total*. INE, 2002. Lisbon. Available at: www.ine.pt

INE. [*Building and Houses Statistics - 2003*]. INE, 2003. Lisbon. Available at www.ine.pt

INE. [*Building and Houses Statistics - 2004*]. INE, 2004. Lisbon. Available at www.ine.pt

Aguiar, R.; Gonçalvez. H; Oliveira, M.; Reis, M. Energy in *Climate Change in Portugal. Scenarios, Impacts and Adaptation Measures - SIAM Project*, F. D. Santos, K. Forbes, R. Moita (eds). Gradiva, Lisbon, 2002.

CELPA. [*Portuguese Paper Industry – 2002 Statistic Notes – Support Statitisc Information*]. *Indústria Papeleira Portuguesa - Boletim Estatístico 2002 – Informação Estatística de Apoio*. CELPA, May 2003.

DGGE. *Personnel communication from Eng. Maria Graça Torres from DGGE Statistics Division*. November 2005.

EDP. [*Technical Report 2001*]. *Relatório Técnico 2001*. EDP, December 2002. Available at: www.edp.pt

EDM. *Personnel communication from Eng. Pontes Leça from EDM – Electricity of Madeira*. October 2005.

ERSE. [*Electric Sector Caracterization – Mainland Portugal*]. *Caracterização do Sector Eléctrico – Portugal Continental*. ERSE 2001. Available at: www.erse.pt

ERSE. *Facts and Numbers – Energetic Framing*. ERSE, 2006. Available at www.erse.pt

IGM. [*Portugal – Extractive Industry*] *Portugal - Indústria Extractiva*. 2000. Available at: http://e-Geo.ineti.pt/geociencias/edicoes_online/diversos/ind_extractiva/indice.htm

INETI [*PNAPRI – National Plan for Industrial Waste Prevention – Guide for Energy Generation, Transmission and Production Sector*]. *PNAPRI – Plano Nacional de Prevenção de Residuos Industriais – Guia do Sector da Produção, Transporte e Distribuição de Energia*. INETI, 2003. Available at: http://www.inresiduos.pt

INE. [*Industrial Production Statistics - 2000*]. INE, 2000b. Lisbon Available at www.ine.pt

LIPOR. *E-mail from Eng. Abílio Almeida to João Cleto* (jfcn@fct.unl.pt). October 2005.

REN. [*Investment Plan for the National Transmission Grid 2006-2011*]. *Plano de investimentos na rede nacional transporte 2006-2011*. REN, 2005. Available at: www.ren.pt

REN. [*Wind Energy in Portugal – 1st Semester 2006*], *Energia Eólica em Portugal – 1º Semestre de 2006*. REN, 2006. Available at www.ren.pt

SEIA. [*Study on the Technical, Legal, Environmental and Socio-Economic Impacts of the implementation of the IPPC Directive in Portugal]. Estudo de identificação e análise das implicações de natureza técnica, económica, social e legal, decorrentes da aplicação em Portugal da Directiva 96/61/CE, relativa à Prevenção e Controlo Integrados da Poluição, commisioned by DGI- Industry General Directorate*. Unpublished. 2000.

PEGOP. [*Pego Power Plant*]. *Central Termoeléctrica do Pego*. 2005. www.pegop.com

Turbogás. *Personnel communication from Eng. Carla Silva from Turbogás*. October 2005.

VALORSUL. [*Valorsul Steam and Energy production]. Produção de Energia e Vapor*. 2005. www.valorsul.pt

REE – Red Eléctrica de España. [*Project Indel – Atlas of the Spanish electricity demand*]. *Proyecto Indel – Atlas de la demanda eléctrica española*. 163 pp. Madrid, 1998. Available at: http://www.ree.es/cap07/pdf/indel/Atlas_INDEL_REE.pdf.

MITYC – Ministerio de Industria, Turismo Y Comercio. [*Spanish Strategy for Energy Saving and Efficiency 2004-2012: Residential and Commercial Sectors*]. *Estrategia de Ahorro y Eficiencia Energética de España 2004-2012: Sector equipamiento residential y ofimática (residencial y servicios).* Spanish Ministry of Industry, Tourism and Commerce, July 2003. Available at: http://www.mityc.es/NR/rdonlyres/0527323B-D56F-4218-BF30-15E21BF01A14/0/AprobacionEstrategia.pdf

IA. *Portuguese National Inventory Report on Greenhouse Gases 1990-2004*. Portuguese Environment Institute. 2006. Available at: www.iambiente.pt

Gonçalves, H., Joyce, A., Silva, L. (eds). [*Renewable Energy in Portugal Forum – a contribution towards the energy and environmental policy objectives – Geothermal*]. *Fórum Energias Renováveis em Portugal - Uma contribuição para os Objectivos de política Energética e Ambiental – Geotermia*. ADENE/INETI, 2002a

Gonçalves, H., Joyce, A., Silva, L. (eds). [*Renewable Energy in Portugal Forum – a contribution towards the energy and environmental policy objectives – solar*]. Fórum *Energias Renováveis em Portugal - Uma contribuição para os Objectivos de política Energética e Ambiental – Solar*. ADENE/INETI, 2002b.

Júlio, S., Cabral, P., Costa, R., Almeida, T. *Characterisation of the potential for electricity conservation in Portugal*. In ECEEE 1997 Summer Study. July 1997, Berlin: Germany

DGGE/ IP-3E. [*Energy efficiency in appliances and electric systems in the residential sector*]. *Eficiência energética em equipamentos e sistemas eléctricos no sector residencial*. DGGE/ IP-3E April 2004. Available at: http://www.p3e-portugal.com/_ficheiros/2/1/Eficiencia.pdf

Enertech et al. *Demand-Side Management - End-use metering campaign in 400 households of the European Community - Assessment of the Potential Electricity Savings*. Project Eureco. January 2002. European Comission - Save Programme.

GPPAA- MADRP. [*Biomass and Renewable Energy in Agriculture, Fisheries and Forestry – Situation in* 2005]. *Biomassa e Energias Renováveis na Agricultura Pescas e Florestas- Ponto da Situação 2005*. Portuguese Ministry of Agriculture Rural Development and Fisheries, Lisbon, 2005.

Gonçalves, H., Joyce, A., Silva, L. (eds). [*Renewable Energy in Portugal Forum – a contribution towards the energy and environmental policy objectives – Biofuels*]. *Fórum Energias Renováveis em Portugal - Uma contribuição para os Objectivos de política Energética e Ambiental – Geotermia*. ADENE/INETI, 2002c

Pinho, M. [*Energy and Climate Change, more investment, better environment*]. *Energia e Alterações Climáticas, mais investimento, melhor ambiente*. Proceedings of the Conference Energy and Climate Change, more investment, better environment. 26th January 2007. Lisbon, Portugal.

Estanqueiro, I. *Data and Statistics on Wind Power Installed in Portugal*. INETI. Lisbon, December 2004

Pinho, P. *The experience and future perspectives of local* players. Proceedings of the Conference Energia e Desenvolvimento Regional. Sines, Portugal. 17th January 2007. Sines, Portugal.

Cruz, J., Sarmento, A. [*Wave Energy - Introduction to technological, economic and environmental aspects*]. *Energia das Ondas - Introdução aos aspectos tecnológicos, económicos e ambientais*. 2004. Instituto do Ambiente.

DGTREN. *European Energy and Transport – Trends to 2030 – Update 2005*. Directorate General for Energy and Transport – European Commission. May 2006. Available: http://ec.europa.eu/dgs/energy_transport/figures/trends_2030_update_2005/energy_transport_trends_2030_update_2005_en.pdf

IA - Instituto do Ambiente. [*Portuguese Report within the article 3, paragraphs 7 and 8 of the Kyoto Protocol*]. *Relatório Inicial de Portugal no âmbito do artigo 3º, parágrafos 7 e 8 do Protocolo de Quioto*. Instituto do Ambiente, Lisbon, 2006b.

Point Carbon. *Carbon 2007 – A New Climate for Carbon Trading*. Roine, K., Hasselknippe, H. (eds.). 62 pages. Point Carbon, 2007.

Kitous, A. *POLES Model - Prospective Outlook on Long Term Energy Systems – A world energy model*. 2006. Available at: http://www.eie.gov.tr/duyurular/EV/twinning/sunular/hafta_02/5_POLES_description.pdf