A low-carbon strategy for Portugal – a hybrid CGE modelling approach

Sara Proença[a, b, *], Miguel St. Aubyn[c]

[a] CERNAS/ESAC, Polytechnic Institute of Coimbra, 3040-316 Bencanta, Coimbra, Portugal
[b, c] Department of Economics, ISEG/TU Lisbon – Technical University of Lisbon,
UECE – Research Unit on Complexity and Economics,
R. Miguel Lupi 20, 1249-078 Lisbon, Portugal

Paper prepared for presentation at the EcoMod 2012 Conference, 4-6 July, Seville

Abstract

Portugal, as an EU Member State, is subject to the EU climate-energy policy regulation and therefore is required to comply with country-specific emission targets to be reached by 2020, as defined in the EU 2020 Climate and Energy Package. In this paper we make use of the Hybrid Bottom-up General Equilibrium Model (HyBGEM) to quantify the economic impacts of a stylized version of Portugal's 2020 low-carbon policy targets under the actual EU emission market segmentation as imposed by the EU Emissions Trading Scheme (EU ETS). In general, simulation results suggest that the national carbon emission reduction targets defined for 2020 can be achieved with potentially low economic adjustment costs.

JEL classification: C63; D58; Q54; Q58.

Keywords: EU climate policy; low-carbon scenarios, emission reduction targets, hybrid CGE modelling; Portuguese economy.

---

[*] Corresponding author. Departamento de Ciências Sociais e Humanas, Escola Superior Agrária/Instituto Politécnico de Coimbra, 3040-316 Bencanta, Portugal. Tel: (+351) 239 802 280; fax: (+351) 239 802 979. E-mail addresses: sproenca@esac.pt (S. Proença); mstaubyn@iseg.utl.pt (M. St. Aubyn).

1. Introduction

The EU 2020 Climate and Energy Package, in force since June 2009, commits the European Union to reduce its overall greenhouse gas (GHG) emissions to at least 20% below their 1990 levels by 2020, pursuing the ambition to make Europe a low-carbon and energy-efficient economy over the next decade. Under the actual EU emission market segmentation, this overall emissions reduction target is split down into a 21% reduction in emissions from the sectors covered by the EU Emissions Trading Scheme (EU ETS) and a 10% reduction in emissions from sectors outside the carbon trading system (non-ETS sectors), taking 2005 as the base year.

Portugal, as an EU Member State, is subject to the EU climate-energy policy regulation and therefore is required to comply with country-specific emission targets by 2020. In particular, Portugal may increase GHG emissions from the non-ETS sectors by 1% compared to 2005 levels by 2020, which must be reached with domestic policy measures. There is no national cap on emissions from the ETS sectors, although a 21% reduction must be achieved jointly across the 27 EU Member States by 2020. Thus, in this study, it is assumed that the EU ETS target applies to Portugal, i.e. Portugal should reduce emissions from the ETS sectors to 21% below 2005 levels by 2020. In the present paper we intend to assess the impacts on the Portuguese economy when complying with this ambitious low-carbon strategy up to 2020.

In our numerical simulations we employ a hybrid top-down/bottom-up modelling approach, which represents a reliable framework to analyse the economy-energy-environment interactions underlying carbon abatement policies. In particular, we make use of the Hybrid Bottom-up General Equilibrium Model (HyBGEM) for Portugal – a multi-sector, CGE model integrating a bottom-up representation of the power sector, which has been designed for energy and climate mitigation policy assessment in a small open economy like Portugal. The HyBGEM model is applied to simulate the effects to achieve Portugal's carbon emission targets defined for 2020, considering as policy instruments (1) the EU ETS with an economy-wide cap-and-trade system for emissions from energy-intensive sectors (ETS sectors), and (2) a domestic carbon tax for emissions from sectors outside the carbon trading system.

The remainder of the paper is organized as follows. Section 2 presents an overview of the HyBGEM model underlying our empirical policy analysis. The low-carbon policy scenario and simulation results are discussed in section 3. Section 4 concludes.

2. HyBGEM model

HyBGEM is a hybrid economy-energy-environment general equilibrium model establishing a top-down/bottom-up integration for highly-disaggregated economic sectors, designed for applied energy and climate policy analysis in a small open economy like Portugal[1]. In particular, the HyBGEM model combines a bottom-up activity analysis representation of the electricity sector with a top-down general equilibrium (CGE) model in a unified framework formulated as a mixed complementarity problem, where the production possibilities in the electricity sector are described by convex combinations of discrete technological options and the other production sectors are characterized by top-down aggregate functional forms usually smooth (nested) constant-elasticity-of-substitution (CES) production functions. This hybrid modelling approach strengthens the robustness of CGE analysis since key technological options for the impact assessment of energy-climate policy measures are explicitly represented based on an engineering foundation.

The HyBGEM model combines a consistent theoretical framework with an observed database covering all interactions between agents in the economy – firms, households,

---

[1] The HyBGEM model development follows as main reference the Policy Assessment based on Computable Equilibrium (PACE) model (see Böhringer *et al.*, 2009 and Böhringer and Rutherford, 2008).

government, and trade flows. It is conceptually built within the Arrow-Debreu (1954) general equilibrium framework, where the competitive market equilibrium is determined by optimization decisions of producers and consumers, satisfying a system of three classes of equilibrium conditions simultaneously: zero profit conditions in all sectors, market clearance conditions for all tradables, and income balance conditions for all households.

2.1 *HyBGEM model structure*

Table 1 provides an overview of the HyBGEM model dimensions for the Portuguese small open economy. The key features of the model are briefly outlined below.

Table 1
HyBGEM model dimensions

	Time Horizon		**2005 – 2020**				
Nr.	**Production Sectors/Commodities**		**Final Demand**	**Primary Factors**		**Regions**	
	Energy		Households	L	Labour	PRT	Portugal
1	COA	Coal	Government	K	Capital	ROW	Rest of the world
2	CRU	Crude oil	Investment	N	Natural resources		
3	GAS	Natural gas	Exports		FF Fossil-fuel resources		
4	OIL	Petroleum and coal products (refined)			Coal, Crude oil, Natural gas		
5	ELE	Electricity			R Renewable resources		
					Water, Wind, Sun, Trees		
	Non-Energy						
6	AFF	Agriculture, forestry, and fishery	**Representative Electricity Generation Technologies**				
7	PPP	Pulp, paper, and print	*Conventional technologies*				
8	CRP	Chemical products	Coal				
9	NMM	Other non-metallic mineral products	Gas, combined-cycle gas turbine (CCGT)				
10	BAM	Basic metals	Oil				
11	MAE	Machinery and equipment	*Renewable technologies*				
12	TEQ	Transport equipment	Hydro				
13	TRD	Trade, repair, and retail	Wind				
14	CNS	Construction	Geothermal				
15	LWT	Land and water transport	Solar PV				
16	ATP	Air transport	Biomass				
17	CGI	Consumer goods industries					
18	TCI	Telecommunication, credit, and insurances					
19	OSR	Other services					

Factors market

Primary factors of production are labour, capital, and natural resources which aggregate fossil-fuel and renewable resources. Initial factors endowments are exogenous. The model assumes perfectly competitive factors market where the prices on factors adjust so that supply equals demand. Labour and capital are assumed to be perfectly mobile across sectors, whereas natural resources are sector-specific. All factors are immobile between counties.

Carbon dioxide (CO_2) emissions

Since carbon dioxide is the most abundant anthropogenic greenhouse gas in the atmosphere and, therefore, the largest contributor to global warming, the HyBGEM focus the analysis on carbon emissions and not to total GHG emissions. It should be noted that the EU energy and climate policies also focus on carbon emissions stemming from fossil-fuels combustion.

Carbon emissions are largely caused by energy related activities primarily the fossil-fuels combustion in production and consumption activities. Thus, CO_2 is introduced in the model as a fixed coefficient (Leontief) input into production and consumption functions such that for each unit of fuel consumed is emitted a known quantity of carbon, where different fuels have different carbon intensities. Given the detailed energy representation in the model, carbon emissions abatement can take place either by reducing the amount of energy per unit of output and consumption (energy savings), or by changing the fuel mix.

Production

The HyBGEM production structure comprises 19 sectors/commodities (5 energy sectors and 14 non-energy sectors)[2]. It is assumed that in each production sector a representative firm minimizes costs of producing output subject to nested constant-elasticity-of-substitution (CES) production functions, which reflect the substitution possibilities in domestic production between inputs of capital (K), labour (L), an energy composite (E), and a material aggregate (M). Each intermediate input represents a composite of domestic and imported varieties – the so-called Armington composite good (see Armington, 1969).

Production of goods other than primary fossil-fuels and bottom-up electricity (Y_g: production of good g) to the domestic and the export market is described by an aggregate production function which characterizes the technology through transformation possibilities on the output side and substitution possibilities on the input side, as illustrated in Annex, Fig. 1. On the output side, production is split between goods produced for the domestic market and goods produced for the export market according to a constant-elasticity-of-transformation (CET) function. On the input side, a three-level CES functions capture the price-dependent use of inputs in production. At the top level, a CES material composite trades off with an aggregate of capital, labour, and energy subject to a constant elasticity of substitution. At the second level, a CES function depicts the substitution possibilities between the energy composite and a value-added aggregate. Finally, at the third level, capital is combined with labour, trading off at a constant elasticity of substitution.

Aggregate material inputs to production of item g are a single level CES function across all non-energy intermediate inputs M, as shown in Annex, Fig. 2.

In the energy composite (E) production structure, energy inputs substitution possibilities are captured by a four-level nested CES function (see Annex, Fig. 3). At the lower nest, fossil-fuel inputs are combined in fixed proportions (Leontief) with CO_2 emissions. At the next level, liquid fuels trade off with a constant elasticity of substitution. This aggregate are combined with coal subject to a CES function in the second level of the nest. Finally, at the top level, the fossil-fuel aggregate (primary energy inputs) combines with electricity at a constant elasticity of substitution.

In the primary fossil-fuels production (FF: coal, crude oil, and natural gas), all non-fuel specific resource inputs (labour, capital, and intermediate inputs) are aggregated in fixed proportions at the lower nest. At the top level, this aggregate trades off with the specific fossil-fuel resource at a CES function (see Annex, Fig. 4). The substitution elasticity between the

---

[2] The HyBGEM sectoral structure has been defined according to our object of applied energy-climate policy analysis. For that purpose we distinguish energy-intensive and carbon-intensive sectors from the rest of the economy wherever available data allows. Furthermore, the data structure has been constructed in line with the nomenclature used in other economy-energy-environment models such as the GTAP-E model, as well as the structure of the Portuguese energy balance and the National Plan for Emission Permits (PNALE) which applies to several significant polluting plants and is included in the EU ETS.

specific factor and the Leontief composite of other inputs (σ_Q) is calibrated in consistency with an exogenously given price elasticity of fossil-fuel supply.

Bottom-up representation of the power generation sector

As in Böhringer and Rutherford (2008), HyBGEM integrates bottom-up activity analysis into a top-down general equilibrium framework through the detailed technological representation of the power production sector[3]. Total electricity production is obtained by a set of discrete electricity generation technologies (t) delivering a homogeneous electricity good, i.e. all power generation technologies produce perfectly substitutable electricity (aggregate electricity good: $ELE = \sum_t ELE_t$). The HyBGEM differentiates eight representative power generation technologies, as follows: three classes of conventional fossil-fuel based electricity generation – coal, gas, and oil –, and five classes of renewable electricity generation – hydro, wind, geothermal, solar PV, and biomass, as depicted in Table 1. Each technology is active or inactive in equilibrium depending on their profitability. The nesting production structure of each electricity generation technology t is defined as a Leontief function of labour, capital, intermediate inputs, and natural resource inputs, as represented in Annex, Fig. 5. It should be underlined that natural resources and capital inputs are technology-specific.

Final Consumption Demand

Final consumption demand is derived from utility maximization of a representative household[4] subject to a budget constraint given by the income level. The nesting structure of final consumption function is represented in Annex, Fig. 6. Consumption demand of the representative agent is represented as a CES aggregate of an energy composite (E) and a non-energy composite good (M). As described above, substitution patterns within the non-energy consumption bundle are reflected via a CES function with an Armington aggregation of imports and domestic commodities (see Annex, Fig. 2); the energy composite consists of the various energy goods trading off at a constant elasticity of substitution (see Annex, Fig. 3). Government demand and investment demand are assumed to be exogenous. Its value is fixed at the benchmark level.

International trade

International trade is modelled assuming two common assumptions in the literature: i) the small open economy assumption, meaning that export and import prices in foreign currency are not affected by the behaviour of the domestic market (i.e., the domestic market is too small to influence world prices, being assumed how price-taker in relation to the ROW[5]), and that the world market can satisfy all the importing and exporting needs of the domestic economy[6]; ii) the Armington´s (1969) assumption of international product differentiation (in the sense that imported and domestically produced goods of the same type are imperfect substitutes) for imports and, symmetrically, the constant-elasticity-of-transformation (CET) supply function for exports, meaning that domestically produced goods may be supplied either to domestic market and export market. The Armington assumption of product heterogeneity means that all goods used on the domestic market in intermediate and final demand correspond to a combination of domestic production and ROW imports with a CES composite function – the so-called

---

[3] It should be noted that the electricity sector is a major source of carbon emissions that has a large mitigation potential through fuel-switching and energy efficiency improvements.

[4] A population of identical households.

[5] Foreign countries are treated as one region termed "Rest of the World" (ROW).

[6] See Shoven and Whalley (1992).

Armington composite good (A_{ig}) – differentiated by demand category g [7], as represented in Annex, Fig. 7. The foreign trade closure requires that the value of imports to the ROW is equal to the value of exports from the ROW after including a constant benchmark trade surplus or deficit. A small open economy is assumed to be price-taker with respect to world market prices (world prices are considered to be exogenous), and hence trade with ROW is represented by perfectly elastic (horizontal) import-supply and export-demand functions.

Model solving

The HyBGEM is numerically implemented as a system of simultaneous non-linear inequalities using the Mathematical Programming System for General Equilibrium analysis as a subsystem within the General Algebraic Modelling System – MPSGE/GAMS (Rosenthal, 2008; Rutherford, 1995, 1999), and solved by using the PATH solve (Ferris and Munson, 2010; Dirkse and Ferris, 1995).

2.2 *HyBGEM model calibration*

The calibration method is adopted in the parameter specification of our comparative-static hybrid CGE model, as usual in applied general equilibrium analysis[8]. Benchmark prices and quantities, jointly with exogenous elasticities determine the free parameters of the functional forms required to model calibration.

The main data source is the GTAP database, version 7, which reconciles economic production, consumption, trade, energy, and carbon emissions data for 113 countries and 57 sectors for the base-year 2004 (Badri and Walmsley, 2008). Given the HyBGEM model dimensions (see Table 1), the GTAP countries are aggregated into Portugal and the rest of the developing world (ROW), compressing the GTAP database to a single-country dataset. At a sectoral level, the GTAP sectors are aggregated into 19 sectors of two main types – 5 energy sectors and 14 non-energy sectors, as listed in Table 1. Power generation by technology is provided by the OECD/IEA Energy Statistics (IEA, 2009). The GTAP 7 2004 reference year is taken in the HyBGEM model as an approximation of the year 2005, which is the base-year of the EU 2020 Climate and Energy Package.

The reference values of the elasticities, as usual in the calibration of applied CGE models, are taken from a review of econometric literature. In particular, elasticities of substitution in sectoral value-added and Armington trade elasticities came from empirical estimates reported in the GTAP 7 database; substitution elasticities between production factors (capital, labour, energy inputs, and material inputs) are based on Okagawa and Ban (2008).

Portugal's baseline growth path over the next 15-years in the absence of carbon emissions constraints, i.e. the business-as-usual (BaU) scenario in 2020 – the target year of the EU climate policy package –, builds on exogenous projections on future GDP levels, sectoral energy input demands with associated carbon emissions, energy prices, and the production structure of the electric power sector. The HyBGEM 2020 BaU scenario is derived from official projections of the US Energy Information Administration – International Energy Outlook 2010 (EIA, 2010), complemented with more detailed data from the OECD/IEA Energy Statistics (IEA, 2009) in Portugal. The GDP growth projections are taken from the Scenarios for the Portuguese Economy 2050 developed by the Portuguese Department of Foresight and Planning and International Affairs (Alvarenga, 2011).

---

[7] The composition of the Armington aggregate good differs across sectors, final consumption demand, investment demand, and public good demand.

[8] See e.g., Mansur and Whalley (1984) and Devarajan *et al.* (1994) for more discussion on the calibration approach.

3. Policy simulations and results

3.1 *Low-carbon scenario definition*

The simulated policy scenario, hereafter mentioned as low-carbon scenario, reflects a stylized version of Portugal's low-carbon policy targets by 2020 under the actual EU emission market segmentation as imposed by the EU Emissions Trading Scheme, as follows[9]:

- Portugal may increase carbon emissions from the non-ETS sectors by 1% compared to 2005 levels by 2020 and should reduce carbon emissions from the ETS sectors to 21% below 2005 levels by 2020.
- There is an economy-wide cap-and-trade system for emissions from energy-intensive sectors (ETS sectors) and the imposition of a uniform domestic carbon tax for emissions from sectors outside the carbon trading system (non-ETS sectors).
- The additional tax revenues from carbon emissions regulation are recycled as lump-sum transfers to households.

The EU ETS comprises the following sectors in the model: coal, crude oil, natural gas, petroleum and coal products (refined), electricity, other non-metallic mineral products, basic metals, pulp-paper-print, chemical products, and air transport. It covers almost half (46.8%) of Portugal's total carbon dioxide emissions, which is in line with the EU ETS Directive.

3.2 *Simulation Results*

This section presents the preliminary results of the simulated low-carbon policy scenario for the Portuguese economy. Simulation results are reported as percentage change from the 2020 business-as-usual (BaU) scenario. The large uncertainties associated with baseline projections and its critical importance for the impact assessment of future policy constraints requires that results be viewed with caution. The results below should therefore be considered as indicative of trends rather than precise values.

The projected patterns of carbon emissions for 2020 are reported in Fig. 1. According to BaU scenario, overall carbon emissions in 2020 will stand roughly 2% above 2005 levels, with the non-ETS sector emissions to decline by 7% and emissions from ETS sector to increase about 11% between 2005 and 2020. Due to the underlying baseline projections for Portugal's carbon emissions in 2020, the nominal and effective emission cutback requirements differ substantially. Table 2 translates Portugal's 2020 low-carbon policy targets compared to 2005 levels into the effective emission abatement requirements from the baseline emissions in 2020. As can be seen, the challenge will be faced by the ETS-sectors, where carbon emissions are expected to continue to increase (in the absence of policy). Non-ETS emissions are projected below 2020 targets.

---

[9] Note that the simulated cap is applied only to carbon emissions from fossil fuel combustion and not to total GHG emissions.

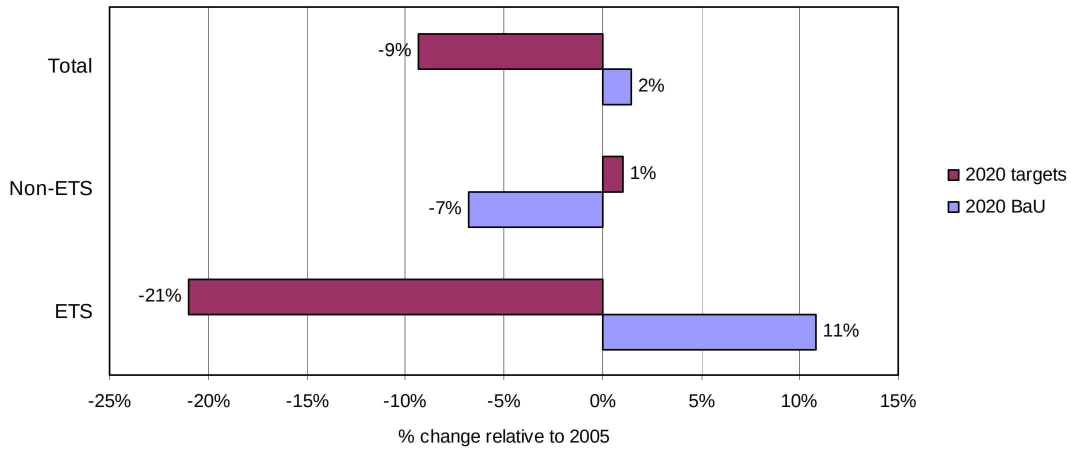

Fig. 1 Changes in carbon emissions in Portugal, 2020 scenarios vis-à-vis 2005 levels

Table 2
Nominal and effective Portugal's carbon emission targets by 2020

	Nominal CO_2 emission targets (% relative to 2005)	Effective CO_2 emission targets (% relative to 2020 BaU)
Total	-9.3	-10.6
ETS	-21.0	-28.7
Non-ETS	1.0	8.3

Fig. 2 reports the simulated carbon emission reduction efforts by sector required to achieve Portugal's 2020 emission targets discussed above. The figure shows that the majority of domestic abatement comes from the electricity sector. Carbon emissions reductions from electricity generation represent a 34.71% share of total abatement in 2020. This reduction results from a modification in the production structure of the national electricity sector with inter-technology and inter-fuel substitution towards low-carbon electricity supply, along with reduced electricity demand. Among the other major sources of carbon abatement, the other non-metallic mineral products sector provides about 7% of abatement in 2020, and the petroleum and coal products and basic metals sectors each have a 6% share of abatement.

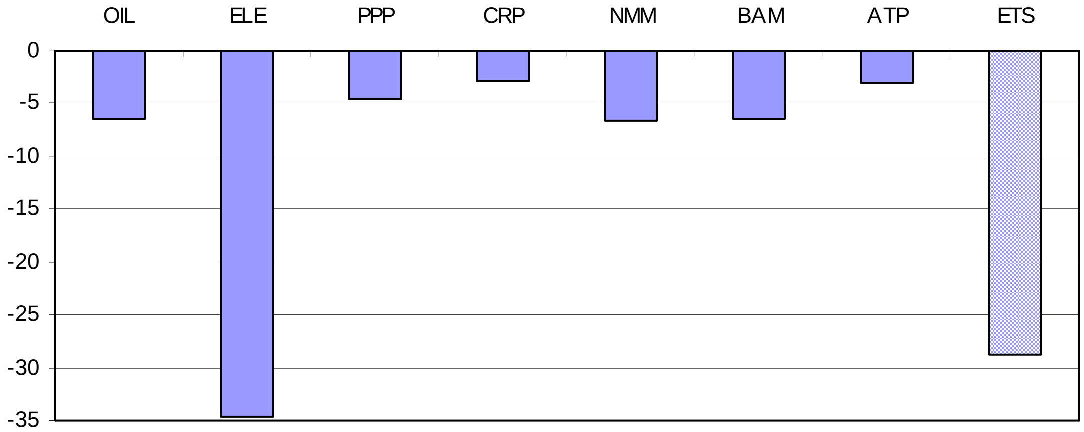

Fig. 2 Sectoral carbon emission reduction efforts (% from 2020 baseline emissions)

Table 3 illustrates results across sectors for some relevant variables. In order to better understand sectorial simulation results, the table also shows benchmark values of energy intensity for each sector. Simulated results suggest that achieving the decarbonisation of the Portuguese economy imposed in the low-carbon policy scenario leads to a contraction in economic activity, reflecting the higher production costs and consequent loss of competitiveness associated with a non-zero carbon price. The price of carbon dioxide emissions is set at around 6 Euros per tonne of CO_2 in 2020.

As expected, the most significant output cutbacks take place in the energy-intensive sectors, in which fossil fuel inputs represent a major share of overall production costs. In this regard, it should be recalled that the carbon emissions are introduced in the HyBGEM model as a fixed coefficient input into production and consumption functions associated with the burning of fossil fuels, such that for each unit of fuel consumed is emitted a known quantity of carbon (where different fuels have different carbon intensities). As coal is the most emissions-intensive fossil-fuel, which is mainly used for domestic electricity generation, our results point out a significant decrease in the coal supply sector, caused by a decline in coal imports (-67.36% from 2020 baseline levels)[10]. This outcome is mainly driven by the contraction in coal demand due to fuel switching toward low-carbon fuels (mainly from coal to natural gas) and renewable energy in the power generation sector. The national power sector, which is predominantly coal-based, experiences an output reduction of 2.93% compared to the BaU levels. The increased costs of electricity supply leads to a raise in electricity prices (+2.69% compared to prices in 2020 without carbon emission caps). In general, there are no noticeable output variations for most non-energy intensive sectors.

Table 3
Sectoral simulation results: effects on prices, output, imports, and exports (% change from 2020 baseline levels)

Sector	BaU level	Low-carbon scenario			
	energy intensity	prices	output	imports	exports
Coal	-	-14.34	-	-67.36	-
Crude oil	-	-14.34	-	-0.52	-
Natural gas	0.65	-14.34	1.35	-0.41	-
Petroleum and coal products (refined)	0.92	-0.02	0.23	-0.51	-0.60
Electricity	0.59	2.69	-2.93	-0.04	-2.93
Agriculture, forestry, and fishery	0.04	-0.09	-0.05	-0.03	-0.05
Pulp, paper, and print	0.03	0.10	-0.42	-0.10	-0.42
Chemical products	0.07	0.14	-0.66	-0.15	-0.66
Other non-metallic mineral products	0.10	0.42	-0.83	-0.03	-0.83
Basic metals	0.04	0.21	-0.90	-0.21	-0.90
Machinery and equipment	0.01	-0.05	-0.19	-0.05	-0.19
Transport equipment	0.01	-0.05	-0.30	-0.05	-0.30
Trade, repair and horeca	0.03	-0.02	-0.08	0.00	-0.08
Construction	0.03	-0.01	-0.05	0.06	-0.05
Land and water transport	0.10	-0.07	-0.21	-0.19	-0.21
Air transport	0.14	0.19	-1.85	-0.17	-1.85
Consumer goods industries	0.02	-0.03	-0.13	-0.02	-0.13
Telecommunication, credit, and insurances	0.01	-0.12	-0.02	-0.02	-0.02
Other services	0.03	-0.09	0.01	0.00	0.01

---

[10] Note that Portugal has not produced coal since its last mine closed in 1994.

Table 4 reports the macroeconomic effects of the simulated low-carbon strategy for Portugal. The induced welfare loss, measured as Hicksian equivalent variation (HEV), is 0.06% from 2020 BaU, reflecting the costs of complying with the national carbon emission targets in 2020. In the new equilibrium, real wages and capital rental rate fall below baseline levels (-0.17% and -0.16%, respectively). The foreign trade closure in the model determines that the overall trade balance remains unchanged compared to the baseline scenario – imports and exports are reduced to the same extent (-0.34%)

Table 4
Simulation results: effects on macroeconomic variables (% change from 2020 baseline levels)

Variable	Low-carbon scenario
Welfare (HEV)	-0.06
Real wage rate	-0.17
Real capital rental rate	-0.16
Imports	-0.34
Exports	-0.34

4. Conclusions

In pursuing the ambition to make Europe a low-carbon and energy-efficient economy over the next decade, in 2009 the EU adopted the so-called 2020 Climate and Energy Package, setting ambitious climate and energy targets to be met by 2020, known as the "20-20-20" targets. The EU committed itself to reduce its total greenhouse gas emissions to at least 20% compared to 1990 levels by 2020. In order to comply with this ambitious target, the EU has launched as main policy instrument a segmented carbon emissions market with an economy-wide cap-and-trade scheme for emissions from energy-intensive sectors and additional domestic policy measures (such as carbon taxes) for emissions from sectors not covered by the EU ETS.

In this paper we examine the economic effects of a stylized version of Portugal’s 2020 carbon emission targets under the actual EU emission market segmentation as imposed by EU ETS. In our numerical impact assessment we used the Hybrid Bottom-up General Equilibrium Model (HyBGEM) – a hybrid economy-energy-environment general equilibrium model establishing a top-down/bottom-up integration for highly-disaggregated economic sectors, designed for applied energy and climate policy analysis in a small open economy like Portugal.

The preliminary simulation results suggest that Portugal can comply with its country-specific carbon emission targets by 2020 without significant compliance costs. The major challenge for policymakers will be to promote an effective decarbonisation of the power sector.

Acknowledgments
The authors acknowledge the Portuguese Science and Technology Foundation for funding the HybCO2 research project, and a PhD scholarship that supports the present work.

References

Alvarenga A, Carvalho P, Lobo A, Rogado X, Azevedo F, Guerra M, Rodrigues S. Long-term Future of the Portuguese Economy - a Scenario Building Process. Departamento de Prospectiva e Planeamento e Relações Internacionais. December 2011, Lisbon, Portugal.

Armington P. A Theory of Demand for Products Distinguished by Place of Production. IMF Staff Papers 1969; 16 (1); 159–178.

Arrow K, Debreu G. The existence of an equilibrium for a competitive economy. Econometrica 1954; 22; 265-269.

Badri G, Walmsley T. Global Trade, Assistance and Production: The GTAP 7 Data Base, Center for Global Trade Analysis, Purdue University, 2008.

Böhringer C, Rutherford T. Combining bottom-up and top-down. Energy Economics 2008; 30 (2); 574-596.

Böhringer C, Löschel A, Moslener U, Rutherford T. EU climate policy up to 2020: An economic impact assessment. Energy Economics 2009; 31 (S2); 295-305.

Devarajan S, Lewis J, Robinson S. Getting the Model Right: The General Equilibrium Approach to Adjustment Policy. Mimeo, 1994.

Dirkse S, Ferris M. The PATH Solver: a non-monotone stabilization scheme for mixed complementarity problems. Optimization Methods and Software 1995; 5; 123–156.

EIA (Energy Information Administration) 2010. International Energy Outlook, Energy Information Administration, US Department of Energy. Available at [http://www.eia.doe.gov/oiaf/ieo].

Ferris C, Munson S. PATH 4.6. GAMS Corporation, 2010. Available at [http://www.gams.com].

IEA (International Energy Agency) 2009. Energy Policies of IEA Countries - Portugal - 2009 Review, OECD/IEA, Paris.

Mansur A, Whalley J. Numerical specification of applied general equilibrium models: estimation, calibration, and data. In: Scarf and Shoven (Eds.), Applied general equilibrium analysis. Cambridge University Press, Cambridge, 1984.

Okagawa A, Ban K. Estimation of Substitution Elasticities for CGE Models. Osaka University, April 2008.

Rosenthal R. GAMS – A User´s Guide, 2008. Available at [http://www.gams.com].

Rutherford T. Extension of GAMS for complementarity problems arising in applied economic analysis. Journal of Economic Dynamics and Control 1995; 19 (8); 1299-1324.

Rutherford T. Applied General Equilibrium Modelling with MPSGE as a GAMS Subsystem: An Overview of the Modelling Framework and Syntax. Computational Economics 1999; 14; 1-46.

Shoven J, Whalley J. Applying General Equilibrium. Cambridge University Press, Cambridge, 1992.

Annex

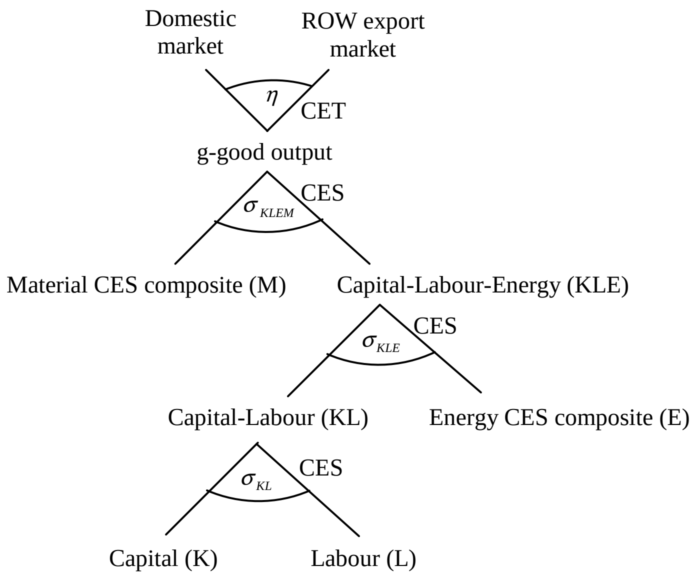

Fig. 1 Nesting CES production structure of goods (other than primary fossil-fuels and technology-specific electricity)

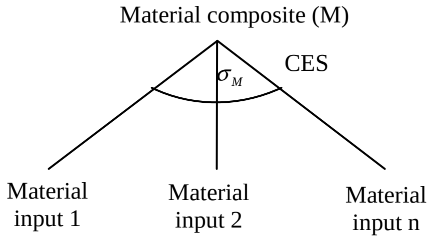

Fig. 2 Nesting CES production structure of sector-specific material composite

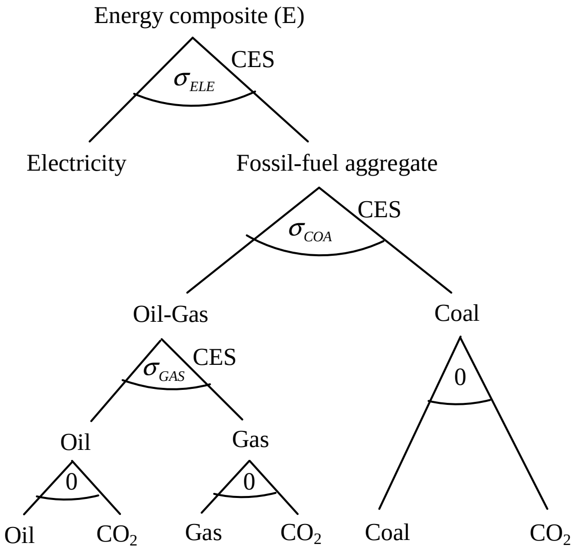

Fig. 3 Nesting CES production structure of sector-specific energy composite

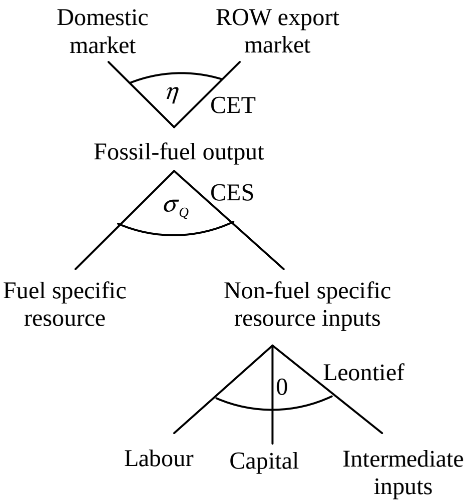

Fig. 4 Nesting CES production structure of fossil-fuels

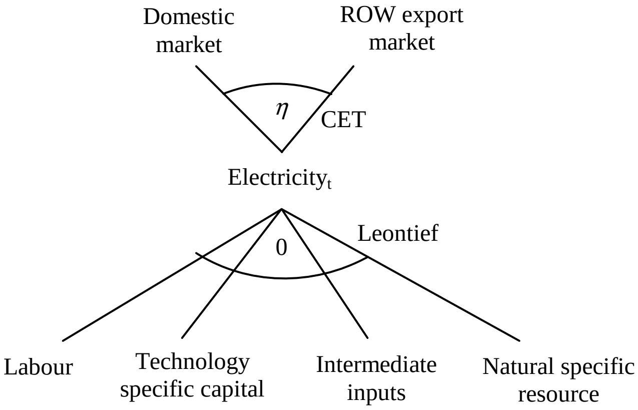

Fig. 5 Nesting production structure of electricity by technology (bottom-up representation of the power sector)

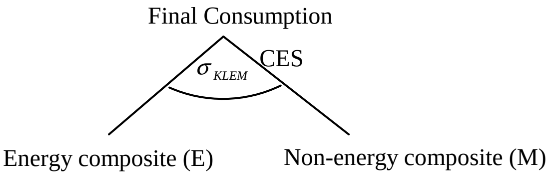

Fig. 6 Nesting structure of final consumption demand

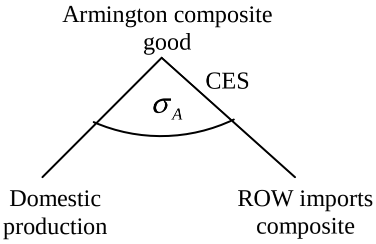

Fig. 7 Nesting CES production structure of Armington composite good