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A hybrid Top-down/Bottom-up model for energy policy analysis in a small open economy - the Portuguese case

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Abstract

Energy/climate change is currently acknowledged by policy makers and the scientific community as one of the major global issues of the worldwide policy agenda.
This paper aims to contribute to the development of a consistent methodology for energy policy analysis, to assist, with decrease uncertainty, policy makers on the design and promotion of cost-effective instruments for climate change mitigation. For this purpose, a hybrid top-down/bottom-up model formulated as a mixed complementarity problem (MCP) will be proposed as a reliable modelling tool to assess the economic effects of different energy policy options in a small open economy. The MCP format permits to join the two modelling forms in a single integrated model, introducing technological detail in general equilibrium models.
The practical suitability of the model is illustrated by an empirical application to the Portuguese case to evaluate the economic impacts of the current Portuguese energy policy promoting electricity from renewable energy sources.

Key words: Economy-energy modelling, top-down and bottom-up, mixed complementarity problems, energy policy analysis.

Thematic Area: Energy, Environment, Transports and Natural Resources Economics

1. INTRODUCTION

Energy and climate issues are today at the top of the political and economic agenda worldwide. In order to achieve energy policy goals of sustainability (low-carbon), security of supply and competitiveness multiple policy instruments are being adopted. Impact assessment of policy instruments plays an important role in the decision-making process. It is particularly relevant for policy makers on the design of cost-effective policy instruments. Methodologically, the impact assessment of energy policy measures have been made in the literature by two modelling approaches: bottom-up (or partial equilibrium) engineering-based models and top-down (mainly computable general equilibrium (CGE) models) economy models. However, both models have specific weaknesses which originate often divergent results, leading to uncertainty in impact assessment and policy design. Top-down models do not include technological detail, overestimating economic adjustments of the energy system, and tend to ignore technological changes induced by prices adjustments. These models help policy makers assess economy-wide policy instruments such as carbon taxes, but are ineffective in assessing the role of technological evolution to achieve a low-carbon economy. Bottom-up models, on the other hand, rely heavily on cost-effectiveness of energy technologies but neglect the macro-economic feedbacks induced by different energy-climate policy instruments, resulting in cost underestimation to achieve environmental goals. Aware of the shortcomings of each model type, recent studies have argued for the need to integrate the two modelling paradigms, combining technological explicitness of bottom-up models with the economic comprehensiveness of top-down models, i.e. developing hybrid models. Three main hybrid approaches have been developed: i) “soft-link” between two independent top-down and bottom-up models through an interactive process among inputs and outputs; ii) link one model to a reduced form of the other, usually link a bottom-up model to a simplified CGE model; iii) Mixed Complementarity Problem (MCP) format to join the two modelling forms in a single integrated model, introducing technological detail in general equilibrium models (e.g., Böhringer and Rutherford, 2008).

In this context, the main purpose of this study is to contribute to the development of a reliable hybrid modelling tool for applied energy policy analysis in a small open economy, in order to assist policy makers on the design and impact assessment of alternative cost-effective energy policy instruments, thereby reducing the uncertainty. For this purpose, a static, multi-sectoral, open, hybrid applied general equilibrium model formulated in the mixed complementarity format will be proposed. The practical suitability of our hybrid MCP model is illustrated by an empirical application for the Portuguese case-study to evaluate the economic effects of a prominent policy measure on the Portuguese energy-climate policy agenda: promoting electricity from renewable energy sources (RES-E).

The remainder of the paper is organized as follows. Section 2 introduces the analytical framework which underlies the merging of hybrid top-down/bottom-up models formulated as a mixed complementarity problem. Section 3 describes in detail the algebraic formulation of the hybrid open MCP model. Section 4 discusses an illustrative empirical application of the model. Section 5 concludes.

2. ANALYTICAL FRAMEWORK

This section introduces the theoretical concepts that underlie the merging of hybrid top-down/bottom-up models formulated as a Mixed Complementarity Problem (MCP). The purpose is to illustrate how the complementarity format can be used in general equilibrium modelling for the hybrid representation of economy-wide production possibilities with a detailed technology description in the energy sectors and top-down functional forms in the other production sectors.

2.1 GENERAL ECONOMIC EQUILIBRIUM MODELS

We assume a competitive Arrow-Debreu (1954) economy with n commodities (goods and factors), m production activities (sectors), and h households (including government). Following the Mathisen´s formulation (1985), the endogenous variables of the general economic equilibrium can be classified into three classes:

- y represents a non-negative m-vector of activity levels of constant-returns-to-scale (CRTS) production sectors ($j = \{1,...,m\}$),
- p is a non-negative n-vector of prices for all goods and factors ($i = \{1,...,n\}$), and
- M is a non-negative k-vector of income levels ($h = \{1,...,k\}$).

A competitive equilibrium in these decision variables satisfies a system of three classes of equilibrium conditions: zero profit condition (quantity condition for all sectors), market clearance condition (price condition for all tradables), and income balance condition (values condition for all households). These three classes of conditions correspond to the general first-order necessary conditions of the producers´ profit maximizing and consumers´ cost minimizing problems, being the core of the general equilibrium problems formulation.

Zero Profit Condition

The first class of equilibrium conditions is based on producers' profit maximization and implies that, in equilibrium, the marginal cost of a commodity cannot be lower than its market price, i.e. no production activity makes a positive profit:

$$-\prod_j(p) = C_j(p) - R_j(p) \geq 0 \quad \forall_j \tag{1}$$

where,

$\prod_j(p)$ represents the unit-profit function for CRTS production sector j, which is calculated as the difference between unit revenue and unit cost functions[1].

In equilibrium, any activity which earns negative unit profits is inactive (i.e. no production activity takes place), hence:

$$y_j \prod_j(p) = 0 \quad \forall_j \tag{2}$$

[1] $R_j(p) \equiv \max\left\{\sum_i p_i \frac{\partial \prod_j}{\partial p_i} \middle| g_j(.) = 1\right\}$; $C_j(p) \equiv \min\left\{\sum_i p_i \frac{\partial \prod_j}{\partial p_i} \middle| f_j(.) = 1\right\}$.

The functions f_j and g_j represents feasible input and output combinations of production in sector j.

Market Clearance Condition

The market clearance condition implies that, for equilibrium prices and activity levels, the supply of any commodity must balance or exceed the demand by consumers:

$$\sum_j y_j \frac{\partial \Pi_j(p)}{\partial p_i} + \sum_h w_{ih} \geq \sum_h d_{ih}(p, M_h) \quad \forall_i \tag{3}$$

where,

$\frac{\partial \Pi_j(p)}{\partial p_i}$ denotes (by Hotelling´s lemma)[2] the compensated supply of good i per unit operation of sector j,

w_{ih} is the initial endowment of household h with commodity i, and

$d_{ih}(p, M_h)$ is the utility maximizing demand function for good i by household h [3].

Any commodity in excess supply has an equilibrium price of zero, hence:

$$p_i\left[\sum_j y_j \frac{\partial \Pi_j(p)}{\partial p_i} + \sum_h w_{ih} - \sum_h d_{ih}(p, M_h)\right] = 0 \quad \forall_i \tag{4}$$

Income Balance Condition

The third class of equilibrium conditions, budget constraint for households, requires that expenditure for each household h does not exceed disposable income:

$$M_h = \sum_i p_i w_{ih} \geq \sum_i p_i d_{ih}(p, M_h) \quad \forall_h \tag{5}$$

Given that underlying utility functions exhibit non-satiation Walras´ law holds[4] and then households are on their budget line, hence:

$$M_h\left(\sum_i p_i w_{ih} - \sum_i p_i d_{ih}(p, M_h)\right) = 0 \quad \forall_h \tag{6}$$

As demonstrated by Mathiesen (1985), in equilibrium any production activity operated at a positive intensity makes zero profit and any production activity which earns a negative net return is inactive. Similarly, any commodity with positive price has a balance between aggregate supply and demand and any commodity in excess supply has an equilibrium price of zero. And, for each household disposable income equals expenditure. This means that the economic equilibrium features complementarity between equilibrium variables and equilibrium conditions: an activity level to a zero profit condition, a commodity price to a market clearance condition, and a consumer income variable to a budget constraint. An equilibrium allocation determines quantities, prices and income levels. Thus, complementarity is a feature rather than a condition for equilibrium in the competitive model. This characteristic of the market equilibrium motivates the formulation of economic CGE models in a mixed complementarity format.

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[2] Hotelling´s lemma: $\frac{\partial \Pi(p)}{\partial p_i} = y_i(p)$, for all $i = 1,...,n$, assuming derivative exists and $p_i > 0$.

[3] $d_{ih}(p, M_h) \equiv \arg\max\left\{U_h(x) \middle| \sum_i p_i x_i = M_h\right\}$, in which U_h denotes the utility function for household h.

[4] As pointed out in Mas-Colell *et al.* (1995): "Walras´ law should be understood broadly: the consumer's budget may be an intertemporal one allowing for savings today to be used for purchases tomorrow. What Walras´law says is that the consumer fully expends his resources over his lifetime."

2.2 GENERAL EQUILIBRIUM AND THE MCP FORMAT

A Mixed Complementarity Problem (MCP) consists of a combination of binding relationships (=) and weak inequalities ($\geq$) and complementarity slackness between system variables and system conditions. Following Rutherford (2002), the MCP format is defined as:

$$
\begin{array}{ll}
\textit{Given} & F : R^n \rightarrow R^n, \quad l, u \in R^n \\
\textit{Find} & z, w, v \in R^n \\
\textit{subject to} & F(z) - w + v = 0 \\
& l \leq z \leq u, \quad w \geq 0, \quad v \geq 0 \\
& w^T (z - l) = 0, \quad v^T (u - z) = 0
\end{array}
\tag{7}
$$

in which $-\infty \leq l \leq u \leq +\infty$, u upper bound and l lower bound, z decision variable, v, w slack variables[5].

The MCP format keeps general equilibrium conditions in its most general form by stating the equilibrium problem as (Böhringer, 1998):

$$
\begin{array}{ll}
\textit{Given} & f : R^n \rightarrow R^n \\
\textit{Find} & z \in R^n \\
\textit{subject to} & f(z) \geq 0,\ z \geq 0,\ z^T f(z) = 0
\end{array}
\tag{8}
$$

which is a special case of MCP format (a nonlinear complementarity problem) by setting $l = 0,\ u = +\infty,\ \textit{and}\ F(z) = f(z)$.

Substituting z by $[y, p, M]$ and $f(z)$ by $\left[\Pi_j(p), \left(\sum_j y_j \frac{\partial \Pi_j(p)}{\partial p_i} + \sum_h w_{ih} + \sum_h d_{ih}\right), \left(\sum_i p_i w_{ih} - \sum_i p_i d_{ih}\right)\right]$ we notice that the complementarity format accommodates equilibrium conditions (1), (3), and (5) as well as the complementarity features (2) and (4) of a general equilibrium problem, showing equivalence of the economic equilibrium problem with the complementarity problem.

The MCP format is particularly useful for mathematical programs which cannot be solved as optimization problems (e.g., problems that include several consumers, taxes, or other market distortions). Then the problem can be turned into a mixed complementarity problem and solved as a system of non-linear equations. However, only if the complementarity problem is "integrable" (see Takayma and Judge, 1971), the solution corresponds to the first-order conditions for a (primal or dual) programming problem. Given integrability, the optimization problem can be interpreted as a market equilibrium problem where prices and quantities are defined using duality theory. In this case, a system of weak inequalities and complementary slackness conditions replace the minimization operator. In particular, the MCP formulation of general equilibrium problems permits integration of bottom-up activity analysis in which alternative technologies may produce one or more products subject to system constraints such as

[5] The expression $x^T y = 0$ means $x_i y_i = 0$, for all $i = 1,\ldots,n.$ The variables x_i and y_i are called a complementary pair and are said to be complements to each other.

carbon emission limits or capacity constraints into a top-down CGE framework, enabling the merging of hybrid models.

3. THE HYBRID MODEL STRUCTURE

Based on the modelling framework described above, this section outlines the specification of a generic hybrid top-down/bottom-up model for energy policy analysis in a small open economy. Following Böhringer and Rutherford (2008), we present a detailed algebraic description of a single integrated model to combine technological detail of a bottom-up energy system with a top-down general equilibrium framework, designed to assess the medium-run effects of different energy policy measures. It is a static, multi-sectoral, applied CGE model for a small open economy formulated in the mixed complementarity format as a non-linear system of inequalities. The functional forms are written in calibrated share form which reduces the efforts as well as sources of errors in the calibration of free function parameters, since it is based on value shares that can be directly read from benchmark prices and quantities without inverting demand functions (Rutherford, 1995).

Following the structure of the Arrow-Debreu model presented in the previous section, the decision variables of our model are defined as follows[6]:

Activity Variables

Y_i denotes the production of non-energy good i,

E_i refers to energy aggregate input in sector i,

FF_i represents the production of fossil-fuel $i \in \{coal, oil, gas\}$,

ELE_t denotes the production of electricity by technology t,

A_i represents the Armington aggregate good i,

U is the utility (consumption and leisure),

C refers to aggregate household final consumption, and

M_i is the world import aggregate of good i.

Price Variables

p_i is the output price of good i produced for the domestic market,

p_i^X is the output price of good i produced for the exported market,

p_i^A is the price of Armington aggregate good i,

p_i^E is the price of energy aggregate in sector i,

w is the labour price,

r_K is the capital price,

r_i is the rent to natural resource i,

p_{ELE} is the electricity price produced for the domestic market,

p_{ELE}^X is the electricity price produced for the exported market,

p_U is the utility price index,

p_C is the price of the household aggregate consumption,

[6] The notation follows closely Böhringer and Rutherford (2008). $\prod_i^x$ represents the profit function of sector i where x is the name assigned to the associated activity.

p_i^M is the price of world import aggregate for good i , and

μ_t is the shadow price on generating capacity.

Income Variable

M is the income of the representative household.

3.1 PRODUCTION

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 capital (K), labour (L), energy goods (E), and non-energy intermediate inputs (M). Each intermediate input M represents a composite of domestic and imported varieties (Armington assumption). Fig. 1 provides a diagrammatic overview of the nesting structure of non-energy goods (Y) production function. Production of non-energy goods (commodities other than fossil fuels and electricity) to the domestic and 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. On the output side, production is split between goods produced for the domestic market and goods produced for the exported market according to a constant-elasticity-of-transformation (CET) function. On the input side, non-energy intermediate inputs (used in fixed coefficients among themselves) are combined in fixed proportions (Leontief production structure) with an aggregate of capital, labour and energy, at the top level. At the second level, a CES function describes the substitution possibilities between the energy aggregate and the value-added aggregate. At last, at the third level, labour is combined with capital, trading off at a constant elasticity of substitution (Cobb-Douglas-CD).

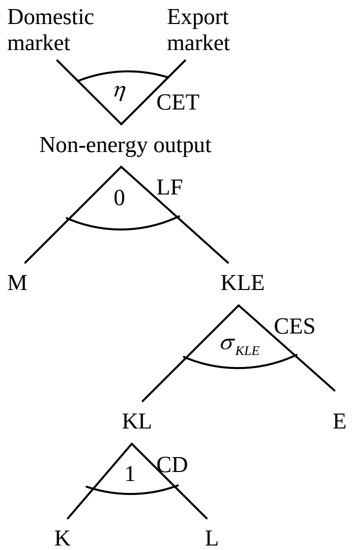

Fig. 1: Nesting structure of non-energy production function

The unit-profit function of non-energy output can be written as:

$$\Pi_i^Y = \left(\theta_i^X \left(p_i^X\right)^{1-\eta} + \left(1-\theta_i^X\right) p_i^{1-\eta}\right)^{\frac{1}{1-\eta}} - \sum_{j \notin E} \theta_{ji} p_j^A - \theta_i^{KLE} \left[\theta_i^E \left(p_i^E\right)^{1-\sigma_{KLE}} + \left(1-\theta_i^E\right)\left(w^{\theta_i^L} r_K^{1-\theta_i^L}\right)^{1-\sigma_{KLE}}\right]^{\frac{1}{1-\sigma_{KLE}}} = 0 \quad \forall_{i,j} \notin E \tag{9}$$

where,

θ_i^X is the value share of ROW exports in sector *i*,

θ_{ji} is the cost share of non-energy intermediate input j in sector i,

θ_i^{KLE} is the cost share of KLE aggregate in sector i,

θ_i^E is the cost share of energy in the KLE aggregate of sector i,

θ_i^L is the labour cost share in sector i,

η is the elasticity of transformation between production for the domestic market and production for the exported market,

σ_{KLE} is the elasticity of substitution between the energy aggregate and the value-added in non-energy production, and

Y is the associated complementary variable.

The energy aggregate (E), in turn, is a nested CES composite of electricity and primary energy inputs, as illustrated in Fig. 2. The fossil-fuel composite is defined as a CES function of coal and a CD aggregate of liquid fuels (LQ) oil and natural gas.

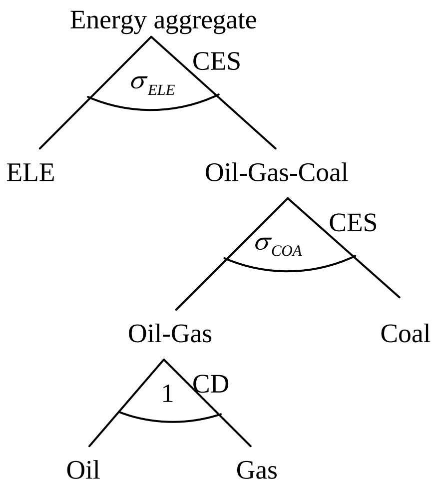

Fig. 2: Nested energy aggregate production structure

The unit-profit function for energy aggregate is:

$$\Pi_i^E = p_i^E - \left\{ \theta_i^{ELE} \left(p_{ELE}^A\right)^{1-\sigma_{ELE}} + \left(1-\theta_i^{ELE}\right) \left[\theta_i^{COA} \left(p_{COA}^A\right)^{1-\sigma_{COA}} + \left(1-\theta_i^{COA}\right) \left(\prod_{j \in LQ} \left(p_j^A\right)^{\beta_{ji}} \right)^{1-\sigma_{COA}} \right]^{\frac{1-\sigma_{ELE}}{1-\sigma_{COA}}} \right\}^{\frac{1}{1-\sigma_{ELE}}} = 0 \tag{10}$$

where,

θ_i^{ELE} is the cost share of electricity in energy demand by sector i,

θ_i^{COA} is the cost share of coal in fossil fuel demand by sector i,

β_{ji} is the share of liquid fossil fuel j in liquid fossil fuel demand by sector i,

σ_{ELE} is the elasticity of substitution between electric and non-electric energy goods (fossil fuel aggregate) in production,

σ_{COA} is the elasticity of substitution between coal and liquid fossil fuel composite in production, and

E is the associated complementary variable.

In the primary fossil-fuels production (FF: coal, oil, and natural gas), all non-fuel inputs (capital, labour, 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. The latter is calibrated in consistency with exogenously given price elasticity of fossil fuel supplies. The structure of fossil-fuel production function is represented in Fig. 3.

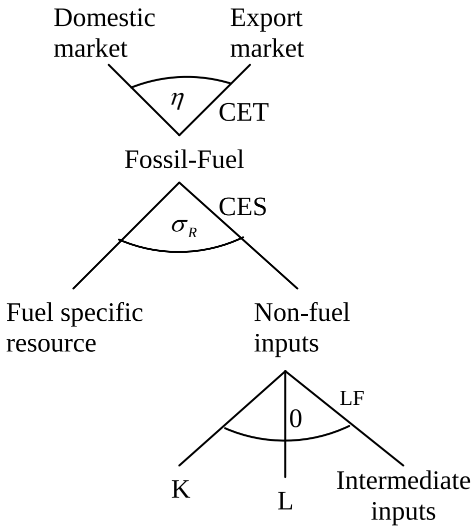

Fig. 3: Nested fossil-fuel production structure

The unit-profit function for fossil-fuel production is:

$$\Pi_i^{FF} = \left(\theta_i^X \left(p_i^X\right)^{1-\eta} + \left(1-\theta_i^X\right) p_i^{1-\eta}\right)^{\frac{1}{1-\eta}} - \left[\theta_i^R r_i^{1-\sigma_{R,i}} + \left(1-\theta_i^R\right)\left(\theta_{Li}^{FF} w + \theta_{Ki}^{FF} r_K + \sum_j \theta_{ji}^{FF} p_j^A\right)^{1-\sigma_{R,i}}\right]^{\frac{1}{1-\sigma_{R,i}}} = 0 \quad \forall_i \in FF \tag{11}$$

where,

θ_i^R is the cost share of fossil-fuel natural resources in sector i,

θ_{Li}^{FF} is the labour cost share in the non-fuel composite input in sector i,

θ_{Ki}^{FF} is the capital cost share in the non-fuel composite input in sector i,

θ_{ji}^{FF} is the cost share of good j in the non-fuel composite input in sector i,

$\sigma_{R,i}$ is the elasticity of substitution between fossil-fuel natural resources and non-fuel inputs in fossil fuel production, and

FF is the associated complementary variable.

As Böhringer and Rutherford (2008), we integrate bottom-up activity analysis into a top-down general equilibrium framework through the detailed technological representation of the electricity production sector (ELE). Therefore, we represent electricity production possibilities by Leontief technologies which are active or inactive in equilibrium depending on their profitability. Fig. 4 provides an overview of the nested electricity production structure.

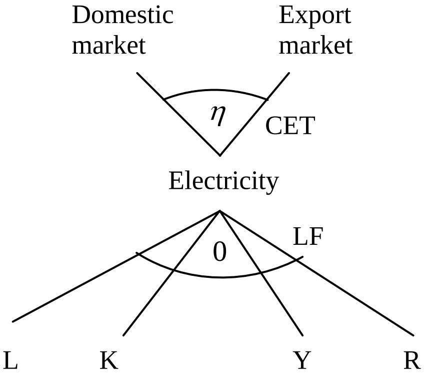

Fig. 4: Nested electricity production structure

The unit-profit function of power generation technology t is:

$$\Pi_t^{ELE} = \left(\theta_{ELE}^X \left(p_{ELE}^X\right)^{1-\eta} + \left(1-\theta_{ELE}^X\right) p_{ELE}^{1-\eta}\right)^{\frac{1}{1-\eta}} - \left(a_t^L w + a_t^K r_K + \sum_{j \notin EG} a_{jt} p_j^A + \sum_i a_{it} \, p_i^A + \mu_t\right) = 0 \quad \forall_i \in R \;\; \forall_j \notin EG \tag{12}$$

where,

θ_{ELE}^X	is the value share of ROW exports in sector ELE ,
a_t^L	is the labour input coefficient in electricity production by technology t,
a_t^K	is the capital input coefficient in electricity production by technology t,
a_{jt}	is the non-energy good input coefficient in electricity production by technology t,
a_{it}	is the natural resource (fossil-fuels and renewable resources) input coefficient in electricity production by technology t, and
ELE	is the associated complementary variable.

3.2 HOUSEHOLDS

We consider a representative consumer agent[7] that maximizes utility subject to a budget constraint given by the income level. The CES utility function is shown in Fig. 5. At the top level, final consumption demand is combined with leisure at a CES function to form an aggregate utility good (i.e., households decide over current versus future consumption). Final consumption demand of the representative agent, in turn, is given by a composite good with a three-level nested CES technology. At the top level, the energy aggregate trades off with non-energy composite good at a CES function. Substitution patterns within the non-energy consumption bundle are reflected via Cobb-Douglas functions with an Armington aggregation of imports and domestic commodities. The fossil-fuel composite is combined at the second level with electricity subject to a CES function. Fossil fuels enter in the third level non-electric energy nest at a unitary elasticity of substitution.

[7] A population of identical households (including government).

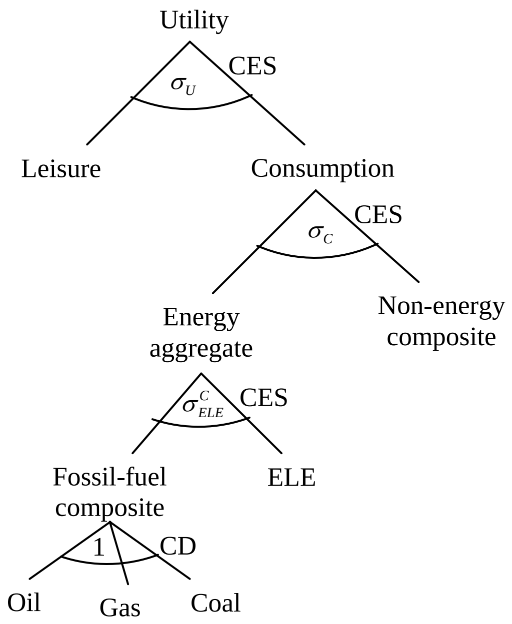

Fig. 5: Utility nested function of representative consumer

The unit-profit function for aggregate utility is:

$$\Pi^U = p_U - \left[\theta_U w^{1-\sigma_U} + (1-\theta_U)(p_C)^{1-\sigma_U}\right]^{\frac{1}{1-\sigma_U}} \tag{13}$$

where,

θ_U is the leisure value share of aggregate utility,

σ_U is the compensated elasticity of substitution between leisure and final consumption, and

U is the associated complementary variable.

The unit-profit function for household final consumption demand is:

$$\Pi^C = p_C - \left\{ \theta_C \left[\prod_{i \notin EG} \left(p_i^A\right)^{\gamma_i} \right]^{1-\sigma_C} + (1-\theta_C) \left[\theta_{ELE}^C \left(p_{ELE}\right)^{1-\sigma_{ELE}^C} + \left(1-\theta_{ELE}^C\right) \left(\prod_{j \in FF} \left(p_j^A\right)^{\varphi_j} \right)^{1-\sigma_{ELE}^C} \right]^{\frac{1-\sigma_C}{1-\sigma_{ELE}^C}} \right\}^{\frac{1}{1-\sigma_C}} = 0 \quad \forall_i \notin EG, \forall_j \in FF \tag{14}$$

where,

θ_C is the cost share of non-energy composite in aggregate household consumption,

θ_{ELE}^C is the cost share of electricity in household energy aggregate demand,

γ_i is the cost share of non-energy good i in non-energy household demand,

φ_i is the cost share of fossil fuel i in non-electric household energy demand,

σ_C is the elasticity of substitution between energy and non-energy goods in household consumption ,

σ_{ELE}^C is the elasticity of substitution between electric and non-electric energy in household energy consumption, and

C is the associated complementary variable.

In our small open economy, the representative consumer agent is endowed with primary factors labour (time) and capital, and natural resources. Thus, total income of the representative household consists of factor payments and scarcity rents on capacity constraints. The income balance of the representative household is then written:

$$M = w\,\overline{L} + r_K\,\overline{K} + \sum_i r_i \overline{R}_i + \sum_t \mu_t \overline{E}LE_t + \overline{B} \tag{15}$$

where,

$\overline{L}$	is the exogenous aggregate endowment with time,
$\overline{K}$	is the exogenous aggregate capital endowment,
$\overline{R}_i$	is the exogenous endowment with natural resource i,
$\overline{E}LE_t$	is the generation capacity for technology t, and
$\overline{B}$	is the balance of payment surplus (deficit).

3.3 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), and that the world market can satisfy all the importing and exporting needs of the domestic economy[8]; ii) the Armington assumption (Armington, 1969) 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 each product variety used on the domestic market in intermediate and final demand corresponds to a combination of domestic production and imports from different regions with a CES composite function, as illustrated in Fig. 6.

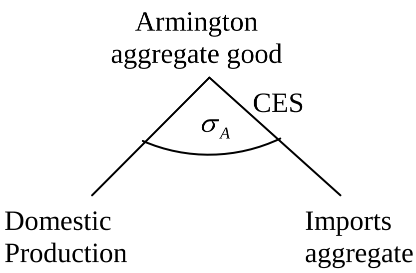

Fig. 6: Nested Armington good

The unit-profit function for Armington aggregate good is:

$$\Pi_i^A = p_i^A - \left[\left(\theta_i^A p_i^{1-\sigma_A} + \left(1-\theta_i^A\right)\left(p_i^M\right)^{1-\sigma_A} \right)^{\frac{1}{1-\sigma_A}} \right] = 0 \tag{16}$$

8 See Shoven and Whalley (1992).

where:

θ_i^A is the cost share of domestic variety i in Armington aggregate good,

σ_A is the Armington substitution elasticity between domestic and imported varieties of the same good, and

A is the associated complementary variable.

Finally, notice that there is an imposed balance of payments constraint to ensure trade. The rest-of-the-world (ROW) 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 (B). 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 included by perfectly elastic ROW import-supply and export-demand functions.

4. APPLICATION OF THE MODEL

The purpose of this section is to illustrate the practical suitability of the hybrid MCP model described above with a simple numerical example based on empirical data for the Portugal case-study for the base-year 2005. We apply our "prototype" model to evaluate the economic effects of a prominent policy measure on the Portuguese energy-climate policy agenda: promoting electricity from renewable energy sources (RES-E).

The sample model describes a small open economy with five production sectors – coal, natural gas (Gas), oil, electricity (Ele), and a macro-good (Y) which represents the rest of economy – whose outputs are demanded by intermediate production, exports and one representative final consumer (Ra). Primary factors include labour (L), capital (K, sector-specific), natural fossil fuel resources (coal, gas, and oil) and natural renewable resources (wind, sun, trees, and water). The electricity production sector covers a set of seven electricity generation representative technologies (coal, gas, oil, hydro, wind, solar, and biomass). The numerical model is implemented as a system of non-linear inequalities using GAMS/MPSGE[9] mathematical programming language (Rosenthal, 2008; Rutherford, 1995, 1999) and solved by using the PATH solver (Dirkse and Ferris, 1995).

4.1. BENCHMARK DATA

The calibration approach is adopted in parameter specification of the model[10], which is calibrated to a single base-year equilibrium such that the model base solution exactly reproduces the values of the adjusted data. This replication characterizes the initial allocation of resources, the so-called benchmark equilibrium. Benchmark prices and quantities, jointly with exogenous elasticities determine the free parameters of the functional forms required to model calibration. The macroeconomic data comes in the form of an aggregate national accounting matrix (NAM), constructed from the integrated system of input-output tables for Portugal for 2005 (DPP, 2008). The final

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[9] General Algebraic Modeling System (GAMS)/Mathematical Programming System for General Equilibrium (MPSGE).

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

NAM[11], shown in Table 1, provides the benchmark data base for the top-down model calibration for Portugal in the base-year 2005. However, to calibrate a hybrid model we have to disaggregate the column in the NAM representing the electric power sector into specific electricity generation technologies (bottom-up engineering data).

Table 1
Benchmark Accounting Matrix for Portugal, 10^6 Euros (NAM-2005)

	Y	Coal	Gas	Oil	Ele	Ra	Exports	Imports	Total Sum
Y	138 499		-178	-356	-976	-147 941	-36 083	47 036	0
Coal	-7				-271	-19		297	0
Gas	-350		1 303	-14	-515	-424			0
Oil	-3 487		-734	4 817	-430	-5 645	-1 117	6 597	0
Ele	-2 984		-5	-3	4 573	-1 837	-93	349	0
Labour	-74 653		-90	-70	-546	75 358			0
Capital	-52 327		-143	4	-1 802	54 267			0
Rent			-147	-4 372		4 519			0
Trf	-4 691		-6	-6	-34	4 766	-28		0
Trade balance						16 956	37 321	-54 278	0
Total Sum	0	0	0	0	0	0	0	0	0

Note: The row Trf represents benchmark transfers between economic agents.

Table 2 and 3 summarize the engineering bottom-up characteristics for the set of electricity generation technologies active in the benchmark equilibrium (coal, gas, oil, and hydro). These data are computed from a range of sources namely the International Energy Agency (IEA) statistics, the TIMES_PT model[12], and the Directorate General for Energy and Geology (DGEG). Given the output share and the cost structure of benchmark active technologies the top-down electric power sector in the NAM is disaggregate into individual electricity supply technologies in a way that is consistent with these technologies´ bottom-up engineering characteristics.

Table 2
Technology Specification Data

Nr.	Technology	Electricity generation GWh	Technology share %	Physical capacity MWh
1	Coal	15 226	33	1 776
3	Gas	13 606	29	2 166
2	Oil	8 791	19	1 909
4	Hydro	8 952	19	6 464
	Total	46 575	100	12 315

Note: The tiny amounts of other renewable technologies (biomass, waste, wind, solar, and geothermal) are accounted for within hydro.

[11] The benchmark NAM is accounted in monetary values (price time quantity) from the national accounts. Then it is not straightforward to distinguish between prices and physical quantities. As usual in the literature, we adopt the Harberger convention, which consists in normalizing all benchmark prices to unity, whereas the amount of production and consumption are set equal to the monetary values in the base accounting matrix (the benchmark values are treated as quantities). Following this convention an Arrow-Debreu economy only depends upon relative prices.

[12] TIMES_PT is a linear optimisation bottom-up technology model, which results from the implementation for Portugal of the model generator TIMES developed by ETSAP (Energy Technology Systems Analysis Programme) of the International Energy Agency. TIMES are the acronym for The Integrated MARKAL-EFOM system. The implementation of the TIMES model for Portugal is being done within the international research project NEEDS (New Energy Externalities Development for Sustainability). The Portuguese research team is responsible for the base-year information, for the validation of technologies information, and for calibration and validation of the national model.

Table 3
Cost Structure of Benchmark Technologies

	Coal	Gas	Oil	Hydro
Ele	1 495	1 336	863	879
Y	-369	-247	-130	-265
Coal	-271			
Gas		-515		
Oil			-430	
Labour	-199	-134	-70	-143
Capital	-656	-440	-232	-471

The elasticity values, as usual in the calibration of CGE models, are taken from review of the relevant literature. Table 4 provides a summary of key elasticities underlying our policy simulations.

Table 4
Summary of Key Elasticities

Production	
Capital-labour vs. Energy aggregate in macro-good production	0.6
Electricity vs. Primary energy inputs (fossil fuel aggregate) in macro-good production	0.3
Fossil fuel inputs in macro-good production	2
Fossil fuel resources vs. Other non-fuel inputs in fossil fuel production	
Coal	0.5
Gas	0.25
Oil	0.25
Consumption	
Consumption vs. Leisure	1.4
Energy vs. Non-energy goods	0.5
Electricity vs. Primary energy inputs (fossil fuel composite)	0.5
Trade	
Domestic production vs. Exported goods (Armington elasticity of transformation)	2
Domestic production vs. Imported goods (Armington elasticity of substitution)	2

Source: Drawn up by authors for this study based on relevant literature - see e.g., GTAP-E (Truong *et al.*, 2007); Kemfert and Welsch (2000); Hertel, 1997; Böhringer and Andreas (2008).

4.2. **POLICY SIMULATION AND RESULTS**

In the policy simulation, we measure the economic effects of Portugal RES-E promotion against a business-as-usual (*BaU*) scenario without political support for renewable energy. According to the Directive 2001/77/EC the RES-E target share to be achieved by Portugal in 2010 is 39% of gross electricity consumption. In January 2007 the Portuguese Government raised voluntarily this target share to 45% in 2010 - we have assumed the RES-E target share in terms of total electricity production. Within this policy background, in the counterfactual policy scenario we impose a cumulative quantity constraint on the share of electricity produced from renewable energy sources at a level which assures compliance with the Portugal RES-E target under the EU obligations. This quantity boundary is related with a complementary uniform endogenous subsidy on renewable electricity generation technologies inactive in the base year (wind, solar, and biomass). We assume that the subsidy is financed by the representative household.

In the *BaU* scenario (year 2005) Portugal renewable energy (i.e. hydro) share in overall power generation amounts to roughly 19%. In our policy simulation, we increase this share gradually in five steps by 20 percentage points up to the Portugal RES-E target share of 39% in 2010.

Simulation results show that the uniform subsidization of renewable power technologies leads to an increase in RES-E deployment, leading to a diversification of energy power supply as can be seen in Figs. 7 and 8. There is a shift from high-carbon fossil fuels technologies such as oil toward carbon-free and high-efficiency power generation technologies such as wind and, consequently, a reduction in CO_2 emissions. The electricity generation from oil decreases more than 50%, which results in a drop of the oil share from by 19% under *BaU* to roughly 8% under the RES-E target share of 39%. The share of wind technology in total electricity generation, in turn, increases from 0% in *BaU* scenario to roughly 23%. Notice, however, that the support scheme for RES-E is not high enough for solar and biomass renewable technologies to break even. Further, the overall level of electricity supply increases by 17% compared with the *BaU* scenario level, leading to a reduction of the electricity imports with positive impacts in terms of security of energy supply.

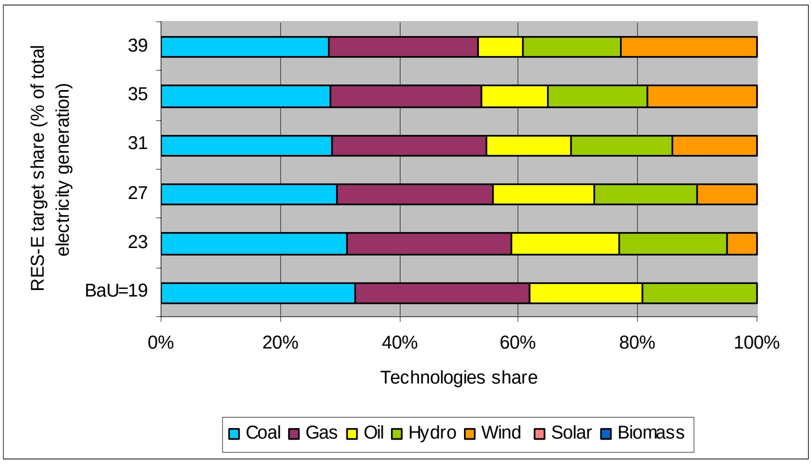

Fig. 7. Impact of RES-E promotion on electricity generation technology mix

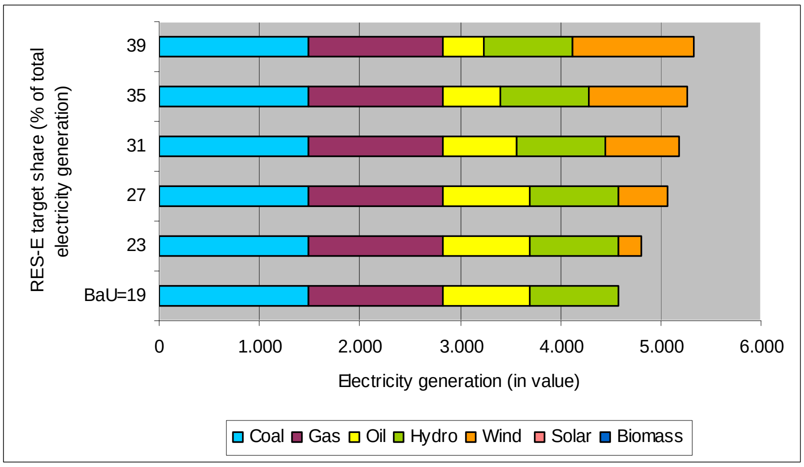

Fig. 8. Impact of RES-E promotion on electricity supply

Fig. 9 illustrates the required subsidy rate to achieve rising RES-E shares from de *BaU* scenario to the Portugal RES-E target share of 39% in 2010, where the subsidy rate is around 45% of electricity price.

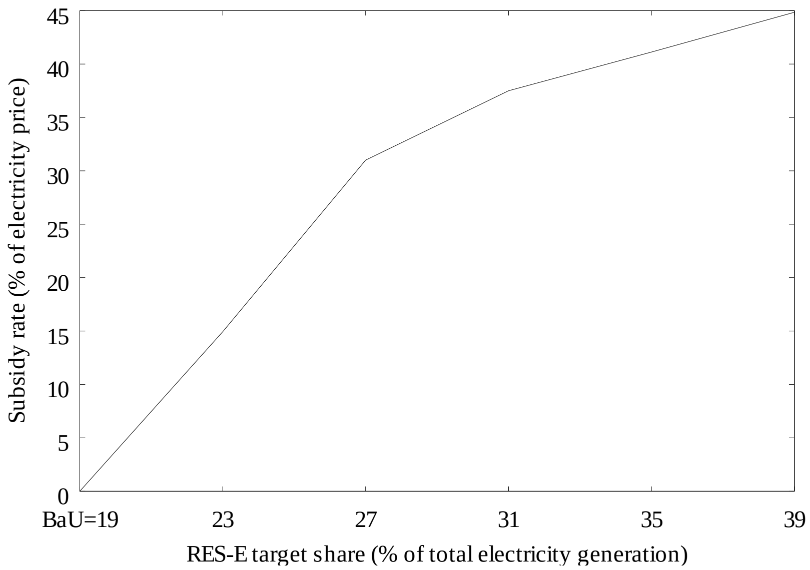

Fig. 9. Subsidy rates of RES-E promotion

The welfare impacts of the RES-E promotion policy are measured in terms of Hicksian equivalent variation (HEV) in income, which captures changes in the economic agent's income induced by the endogenous subsidy. As shown in Fig. 10, the welfare effects are negative. The extent of welfare losses is closely related to the RES-E share value, wherein a share of 39% leads to an income loss of roughly -0.14%. Notice, however, that such induced income losses should be compared with the welfare gains from positive environmental externalities, e.g. from lower CO_2 emissions. Yet, no such effects are captured by the model.

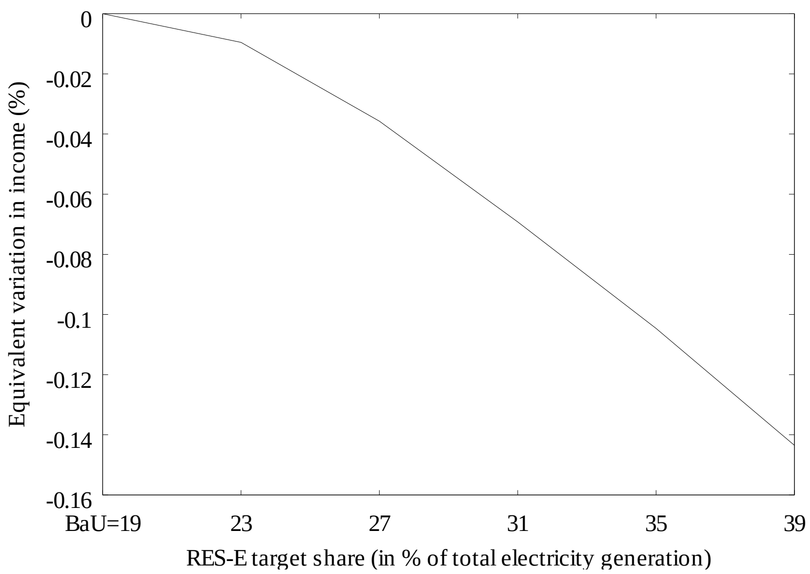

Fig. 10. Welfare effects of RES-E promotion

5. CONCLUSIONS

Conventional top-down and bottom-up models have inherent weaknesses which limited their usefulness to police-makers in energy policy analysis. Accordingly, policy modellers have explored the development of a new generation of hybrid energy-environment-economy models which contains both technological foundation of bottom-up models and the economic richness of top-down general equilibrium models.

In this paper, we have motivated the development of a hybrid top-down/bottom-up modelling tool for energy policy analysis in a small open economy, formulated as a mixed complementarity problem. The MCP format permits to join the two modelling forms in a single integrated model, introducing technological detail in general equilibrium models. A static, multi-sectoral, applied hybrid general equilibrium MCP model is presented as a reliable modelling tool to assess the economic effects of alternative energy policy measures. The economic costs induced by energy-climate policies can be substantially reduced if an assessment is made of the cost-effectiveness of alternative policy instruments and technological options. This impact assessment can be properly made by using this type of modelling approach, which can be applied to a wide variety of policy analysis and countries.

The practical suitability of the model is illustrated by a simple numerical application for the Portuguese case-study, analysing the economic effects of Portugal RES-E promotion. Our simulation results show that the uniform subsidization of renewable power technologies require relatively modest adjustment costs to the Portuguese economy.

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