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**Working Paper**

## Integrating Bottom-Up into Top-Down: A Mixed Complementarity Approach

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## **Nontechnical Summary**

In applied energy policy analysis there is a commonly perceived dichotomy between bottom-up models of the energy system and top-down models of the overall economy. Bottom-up models provide a detailed description of the energy system from primary energy processing via multiple conversion, transport, and distribution processes to final energy use but neglect interactions with the rest of the economy. Furthermore, the formulation of such models as mathematical programs restricts their direct applicability to integrable equilibrium problems; many interesting policy problems involving initial inefficiencies can therefore not be handled directly. Top-down economy-wide models on the other hand are able to capture market interactions and inefficiencies in a comprehensive manner but typically lack technological details that might be relevant for the policy issue at hand.

In this paper, we motivate the formulation of market equilibria as a mixed complementarity problem (MCP) in order to bridge the gap between bottom-up and top-down analysis. Through the explicit representation of weak inequalities and complementarity between decision variables and functional relationships, the MCP approach allows to exploit the advantages of each model type – technological details of bottom-up models and economic richness of top-down models – in a single mathematical format.

We demonstrate the integration of bottom-up into top-down along a simple stylized example and present illustrative policy simulations with our integrated model on central energy policy issues including green quotas, nuclear phase-out, and carbon taxation. Together with an explicit algebraic representation, we provide the computer programs for the replication of simulation results. The latter may serve as a starting point for further – more elaborate – applications by the interested reader.

# Integrating Bottom-Up into Top-Down: A Mixed Complementarity Approach

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## Abstract

We motivate the formulation of market equilibria as a mixed complementarity problem (MCP) in order to bridge the gap between bottom-up energy system models and top-down general equilibrium models for energy policy analysis. Our objective is primarily pedagogic. We first lay out that the MCP approach provides an explicit representation of weak inequalities and complementarity between decision variables and market equilibrium conditions. This permits us to combine bottom-up technological details and top-down economic richness in a single mathematical format. We then provide a stylized example of how to integrate bottom-up features into a top-down modeling framework along with worked examples and computer programs which illustrate our approach.

**JEL classification:** C61, C68, D58, Q43

**Keywords:** Energy Policy, Computable General Equilibrium, Bottom-Up, Top-Down

# 1 Introduction

There are two wide-spread modeling approaches for the quantitative assessment of economic impacts induced by energy policies: bottom-up energy system models and top-down models of the broader economy. The two model classes differ mainly with respect to the emphasis placed on technological details of the energy system vis-à-vis the comprehensiveness of endogenous market adjustments.

Bottom-up energy system models are partial equilibrium representations of the energy sector. They feature a larger number of discrete energy technologies to capture substitution of energy carriers on the primary and final energy level, process substitution, process (efficiency) improvements, or energy savings but omit interaction with the rest of the economy. These models are typically cast as optimization problems that compute the least-cost combination of energy system activities to meet a given demand for final energy or energy services subject to technical restrictions and energy policy constraints.

Top-down models adopt a broader economic framework taking into account interaction and spillover effects between markets as well as income effects for various economic agents such as private households or the government. The high degree of endogeneity in economic responses to policy shocks typically goes at the expense of specific sectoral or technological detail. As a matter of fact, conventional top-down models of energy-economy interactions have a very skimpy representation of the energy system: Energy transformation processes are represented by smooth production functions which capture abstract substitution (transformation) possibilities through constant elasticities of substitution (transformation). Consequently, top-down models usually lack detail on current and future technological options which may be relevant for an appropriate assessment of specific energy policy proposals.<sup>1</sup>

The specific strengths and weaknesses of the bottom-up and top-down framework explain continuous hybrid modeling efforts that combine technological explicitness of bottom-up models with the economic richness of top-down models. There are three major approaches to hybridizing: First, existing – independently developed – bottom-up and top-down models can be linked. This approach has been adopted since the early 1970ies (see e.g. Hofman and Jorgenson [1976], Hogan and Weyant [1982], or Messner and Strubegger [1987]) but often challenges overall coherence due to inconsistencies in behavioral assumptions and accounting concepts of "soft-linked" models. Second, one could focus on one model type – either bottom-up or top-down – and use "reduced form" representations of the other. A prominent example along this line is ETA-Macro (Manne [1977]) which links a detailed bottom-up energy system model with a highly aggregate one-sector macro-economic model of production and consumption within a single optimization framework.<sup>2</sup> The third approach provides

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<sup>1</sup>In addition, top-down models may not assure fundamental physical restrictions such as the conservation of matter and energy.

<sup>2</sup>More recent hybrid modelling approaches based on the same technique include Bahn et al. [1999] or Messner and Schrattenholzer [2000].

completely integrated models (see e.g. Böhringer [1998]) based on developments of solution algorithms for mixed complementarity problems during the mid90ies (Dirkse and Ferris [1995], Rutherford [1995]).

In this paper, we focus on the integrated mixed complementarity approach which stands out for the coherence and logical appeal to bridging the gap between conventional bottom-up energy system models and top-down computable general equilibrium (CGE) models for energy policy analysis.<sup>3</sup> Apart from accommodating discrete activity analysis with respect to alternative technological options in an economy-wide framework, the mixed complementarity approach relaxes so-called "integrability" conditions that are inherent to bottom-up models or integrated system models formulated as optimization problem. In applied energy policy analysis it is often overlooked that optimization problems are only equivalent to economic market equilibrium problems subject to integrability conditions that imply efficient allocation (Pressman [1970] or Takayma and Judge [1971]). Since many interesting economic problems are associated with non-integrable second-best situations (due to ad-valorem taxes, institutional price constraints, or spillover externalities), the optimization approach to integrate bottom-up and top-down is relatively limited in the scope of policy applications.<sup>4</sup>

Our objective is primarily pedagogic. We start by motivating the formulation of market equilibria as a mixed complementarity problem (MCP). The MCP formulation explicitly features weak inequalities and complementarity between decision variables and market equilibrium conditions: This permits the modeler to combine the advantages of bottom-up technological details and top-down economic richness in a single mathematical format. We then lay out the integration of a stylized bottom-up representation for electricity generation into a simple top-down description of the wider economy. Finally, we present illustrative policy simulations with our integrated model on central energy policy issues including green quotas, nuclear phase-out, or carbon taxation. Along with an algebraic representation, we provide the computer programs for the replication of simulation results. The latter may serve as a potential starting point for further more elaborate applied analysis by the interested reader.

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<sup>3</sup>Apart from CGE models that adopt the (neoclassical) microeconomic rationale, top-down approaches may also include aggregate demand-driven Keynesian models which typically put more emphasis on macroeconomic phenomena and econometric foundations (see Weyant and Olavson [1999]).

<sup>4</sup>"Non-integrabilities" furthermore reflect empirical evidence that individual demand functions depend not only on prices but also on the initial endowments. In such cases, demand functions are typically not "integrable" into an economy-wide utility function (see e.g. Chipman [1974]): Only if the matrix of cross-price elasticities (i.e. the first-order partial derivatives of the demand functions) be symmetric, is there an associated optimization problem which can be used to compute the equilibrium prices and quantities.

## 2 Mixed Complementarity Formulation of Market Equilibria

We consider a competitive (*Arrow-Debreu*) economy with  $n$  commodities (incl. factors),  $m$  production activities (sectors), and  $h$  households. The decision variables of the economy can be classified into three categories (Mathiesen [1985]):

- $p$  is a non-negative  $n$ -vector (with running index  $i$ ) in prices for all goods and factors
- $y$  denotes a non-negative  $m$ -vector (with running index  $j$ ) for activity levels of constant-returns-to-scale (CRTS) production sectors, and
- $M$  represents a non-negative  $k$ -vector (with running index  $h$ ) in incomes.

A competitive market equilibrium is characterized by a non-negative vector of activity levels ( $y \geq 0$ ), a non-negative vector of prices ( $p \geq 0$ ), and a non-negative vector of incomes ( $M \geq 0$ ) such that:

- No production activity makes a positive profit (zero-profit condition), i.e.:

$$-\Pi_j(p) = -a_j^T(p)p \geq 0 \quad (1)$$

where:

$\Pi_j(p)$  denotes the unit profit function for CRTS production activity  $j$ , which is calculated as the difference between unit revenue and unit cost, and

$a_j^T(p)$  is the price-dependent technology vector for activity  $j$  which by – Hotelling’s Lemma – corresponds to the the partial derivate  $\nabla \Pi_j(p)$ .<sup>5</sup>

- Excess supply (supply minus demand) is non-negative for all goods and factors (market clearance condition), i.e.:

$$\sum_j y_j \nabla \Pi_j(p) + \sum_h w_h \geq \sum_h d_h(p, M_h) \quad (2)$$

where:

$w_h$  indicates the initial endowment vector of household  $h$ , and

$d_h(p, M_h)$  is the utility maximizing demand vector for household  $h$ .

- Expenditure for household each  $h$  does not exceed income (budget constraint), i.e.:

$$M_h = p^T w_h \quad (3)$$

Using Walras’ law, we can transform equilibrium conditions (1)-(3) to yield:

$$y_i \Pi_j(p) = 0 \quad (4)$$

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<sup>5</sup>Input coefficients have a negative sign; output coefficients are positive.



$$p_i \left[ \sum_j (y_i \nabla \Pi_j(p) + \sum_h w_h) - \sum_h d_h(p, M_h) \right] = 0 \quad (5)$$

$$M_h(M_h - p^T w_h) = 0 \quad (6)$$

Thus, economic equilibrium features complementarity between equilibrium variables and equilibrium conditions: (i) positive market prices imply market clearance, otherwise commodities are in excess supply and the respective prices fall to zero; (ii) activities will be operated as long as they break even, otherwise production activities are shut down; and (iii) income variables are linked to income budget constraints.

The complementarity features of economic equilibrium motivate the formulation of market equilibrium problems as a mixed complementarity problem (Rutherford [1995]):<sup>6</sup>

$$\text{Given } f: R^N \rightarrow R^N, l, u \in R^N$$

$$\text{Find } z, w, v \in R^N$$

subject to

$$F(z) - w + v = 0$$

$$l \leq z \leq u, w \geq 0, v \geq 0,$$

$$w^T(z - l) = 0, v^T(u - z) = 0$$

We obtain the formulation of our market equilibrium as a mixed complementarity problem (MCP) by setting  $l = 0$ ,  $u = +\infty$ ,  $z = [y, p, M]$ , and letting  $F(z)$  depict the equilibrium conditions (1)-(3). The MCP formulation provides a flexible framework for the integration of bottom-up activity analysis where alternative technologies  $t$  can produce the same output subject to technology-specific capacity constraints. As a concrete example, we may consider the standard linear planning problem to find a least-cost supply schedule for meeting an exogenous demand in energy good (service)  $j$ :

$$\min \sum_i \sum_t p_i a_{ijt} y_{jt} \quad (7)$$

subject to

$$\begin{aligned} \sum_t y_{jt} + \sum_{i \neq j} a_{ji} \bar{y}_i + \sum_h w_{jh} &\geq \sum_h \bar{d}_{jh} \\ y_{jt} &\leq \sum_h w_{hjt} \end{aligned}$$

where:

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<sup>6</sup>The term "mixed complementarity problem" (MCP) reflects central features of this mathematical format: "mixed" indicates that the MCP formulation includes equalities as well as inequalities; "complementarity" refers to complementary slackness between system variables and system conditions.

$y_{jt}$  is the activity level of technology  $t$  producing energy good  $j$ ,

$a_{ijt}$  denotes the (fixed) input coefficient for good  $i$  of technology  $t$  producing energy good  $j$ ,

$\bar{d}_{jh}$  represents the exogenous demand by household  $h$  for energy good  $j$ ,

$\bar{y}_i$  is the exogenous level of non-energy production activity  $i$ , and

$w_{hjt}$  is the capacity of technology  $t$  producing energy good  $j$  which is owned by household  $h$ .

When we derive the Kuhn-Tucker conditions of the linear program, we obtain:

$$-(\sum_i a_{ijt} p_i + \lambda_{jt}) - \pi_j \geq 0, \quad y_{jt}, \quad y_{jt} [-(\sum_i a_{ijt} p_i + \lambda_{jt}) - \pi_j] = 0 \quad (8)$$

$$\sum_t y_{jt} + \sum_i a_{ji} \bar{y}_i + \sum_h w_{jh} \geq \sum_h \bar{d}_{jh}, \quad \pi_j, \pi_j (\sum_t y_{jt} + \sum_i a_{ji} \bar{y}_i + \sum_h w_{jh} - \sum_h \bar{d}_{jh}) = 0 \quad (9)$$

$$y_{jt} \leq \sum_h w_{hjt}, \quad \lambda_{jt}, \quad \lambda_{jt} (\sum_h w_{hjt} - y_{jt}) = 0 \quad (10)$$

where:

$\pi_j$  is the shadow price on the supply-demand balance for energy good  $j$ , and

$\lambda_{jt}$  is the shadow price on the capacity constraint for technology  $t$  producing energy good  $j$ .

Comparing the Kuhn-Tucker conditions with the MCP formulation of our market equilibrium problem, we see that both are equivalent as the shadow prices of programming constraints coincide with market prices. The linear mathematical program can be readily interpreted as a special case of the general equilibrium problem where (i) income constraints are dropped, (ii) energy market demand of the non-energy system is exogenous, and (iii) energy supply technologies are characterized by fixed coefficients (rather than price-responsive coefficients). In turn, we can replace an aggregate top-down description of energy good production in the general equilibrium market setting with the Kuhn-Tucker conditions of the linear program which provides technological details.

Beyond the direct integration of bottom-up activity analysis, we can extend the MCP formulation of market equilibrium by adding explicit bounds on decisions variables such as prices or activity levels. Examples for price constraints may include lower bounds on the real wage or prescribed price caps on energy goods (upper bounds). As to quantity constraints, examples may include administered bounds on the share of specific energy sources (e.g. renewables or nuclear power) or target levels for the provision of public goods. Associated with these constraints, are complementary variables: In the case of price constraints, a rationing variable applies as soon as the price constraint becomes binding; in the case of quantity constraints, a complementary endogenous subsidy or tax is introduced.

### 3 Integration of Bottom-up into Top-Down: A Simple Maquette

In order to illustrate the MCP integration of bottom-up technological details into a top-down general equilibrium framework, we consider a stylized static closed economy.

On the production side, firms minimize costs of producing output subject to nested constant-elasticity-of-substitution (CES) functions that describe the price-dependent use of factors and intermediate input. In the production of some macro good  $ROI$ , capital and electricity inputs trade off in the lower nest. The capital-electricity composite is then combined at the top-level with labor. The unit-profit function of macro-good production ( $i \in ROI$ ) reads as:

$$\Pi_i^Y = p_i - \{(\theta_{L,i}p_L)^{1-\sigma} + (1 - \theta_{L,i})[\theta_{ELE,i}p_{ELE}^{1-\sigma_{ELE,i}} + (1 - \theta_{ELE,i})p_K^{1-\sigma_{ELE,i}}]^{\frac{1-\sigma}{1-\sigma_{ELE,i}}}\}^{\frac{1}{1-\sigma}} \quad (11)$$

where:

$p_i$  is the price of good  $i$ ,

$p_L$  refers to the price of labor,

$p_{ELE}$  denotes the electricity price,

$p_K$  represents the price of capital,

$\theta_{L,i}$  is the cost share of labor in production of good  $i$ ,

$\theta_{ELE,i}$  represents the cost share of electricity in the sector-specific capital-electricity composite,

$\sigma$  is the elasticity of substitution between labor and non-labor inputs, and

$\sigma_{ELE,i}$  is the elasticity of substitution between electricity and capital.

In the production of fossil fuels – here: coal, gas, and oil – all inputs, except for the sector-specific fossil-fuel resource, are aggregated in fixed proportions at the lower nest. At the top level this aggregate trades off with the sector-specific fossil fuel resource at a constant elasticity of substitution.<sup>7</sup> The unit-profit function for fossil fuel production ( $i \in FF$ ) is:

$$\Pi_i^Y = p_i - \{\theta_i p_{Q,i}^{1-\sigma_i} + (1 - \theta_i)[\theta_{ROI,i}p_{ROI} + (1 - \theta_{ROI,i})p_L]^{1-\sigma_i}\}^{\frac{1}{1-\sigma_i}} \quad (12)$$

where:

$p_{Q,i}$  represents the price of the fossil fuel resource ( $i \in FF$ ),

$p_{ROI}$  is the price of the  $ROI$  macro good,

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<sup>7</sup>The latter can then be calibrated in consistency with empirical estimates for price elasticities of fossil fuel supply.

$\theta_i$  denotes the cost share of the fossil fuel resource,

$\theta_{ROI,i}$  refers the cost share of the *ROI* macro good in the aggregate input of *ROI* and labor,  
and

$\sigma_i$  is the elasticity of substitution between the fossil fuel resource and the *ROI*-labor composite.

In our stylized example, we illustrate the integration of bottom-up activity analysis into the generic top-down representation of the overall economy along the example of the electricity sector. Rather than describing electricity generation by means of a single continuous smooth CES production function we capture production possibilities by discrete (Leontief) technologies that are active or inactive in equilibrium depending on their profitability. The detailed technological representation may be necessary for an appropriate assessment of specific policy proposals. For example, energy policies may prescribe target shares of specific technologies in overall electricity production (such as green quotas) or the gradual elimination of certain power generation technologies (such as a nuclear phase-out). We can write the unit-profit functions of discrete power generation technologies as:

$$\Pi_t^{ELE} = p_{ELE} - \theta_{ROI,t}p_{ROI} - \theta_{K,t}p_K - \sum_{i \in FF} \theta_{i,t}p_i - p_{U,t} \quad (13)$$

where:

$p_{U,t}$  is the shadow price (rental rate) on the upper capacity bound for technology  $t$ ,

$\theta_{ROI,t}$  denotes the cost share of *ROI* in electricity production by technology  $t$ ,

$\theta_{K,t}$  refers to the cost share of capital in electricity production by technology  $t$ , and

$\theta_{i,t}$  represents the cost share of fossil fuel  $i$  ( $i \in FF$ ) in electricity production by technology  $t$ .

Finally, a composite consumption good is produced subject to a two-level CES technology where electricity and oil trade off at the second level and the electricity-oil composite is then combined with the macro good at the top level. The unit-profit function for the production of the final consumption good is:

$$\begin{aligned} \Pi^C = & p_C - \{ \theta_{ROI,C} p_{ROI}^{1-\sigma_C} + (1 - \theta_{ROI,C}) [\theta_{ELE,C} p_{ELE}^{1-\sigma_{ELE,C}} \\ & + (1 - \theta_{ELE,C}) p_{OIL}^{1-\sigma_{ELE,C}}]^{\frac{1-\sigma_C}{1-\sigma_{ELE,C}}} \}^{\frac{1}{1-\sigma_C}} \end{aligned} \quad (14)$$

where:

$p_C$  is the price of the final consumption composite,

$p_{OIL}$  denotes the price of oil,

$\theta_{ROI,C}$  represents the cost share of *ROI* in the final consumption aggregate,

$\theta_{ELE,C}$  refers to the cost share of electricity in the oil-electricity composite of final consumption,

$\sigma_C$  is the elasticity of substitution between energy and non-energy inputs in final consumption, and

$\sigma_{ELE,C}$  denotes the elasticity of substitution between electricity and oil within the oil-electricity composite of final consumption.

In our stylized economy, a representative household is endowed with primary factors labor, capital, and fossil fuel resources (used for fossil fuel production). Total income of the household consists of factor payments:

$$M = p_L \bar{L} + p_K \bar{K} + \sum_{i \in FF} p_{Q,i} \bar{Q}_i + \sum_t \bar{U}_t p_{U,t} \quad (15)$$

where:

$M$  is the income of the representative household,

$\bar{L}$  denotes the aggregate labor endowment,

$\bar{K}$  represents the aggregate capital endowment,

$\bar{Q}_i$  refers to the resource endowment with fossil fuel ( $i \in FF$ ), and

$\bar{U}_t$  denotes the available capacity for technology  $t$ .

The representative household maximizes utility from consumption subject to available income.

Flexible prices on competitive markets for factors and goods assure balance of supply and demand <sup>8</sup> Using Hotelling's lemma, we can derive compensated supply and demand functions of goods and factors on the producer side. Composite consumption of the representative household is given by Roy's identity.

Market clearance conditions for our stylized economy then read as:

- Labor market clearance:

$$\bar{L} \geq \sum_i \frac{\partial \Pi_i^Y}{\partial p_L} Y_i + \sum_t \frac{\partial \Pi_t^{ELE}}{\partial p_L} X_t + \frac{\partial \Pi^C}{\partial p_L} C \quad (16)$$

where:

$Y_i$  denotes the level of production of good  $i$  (except for electricity),

$C$  is the level of aggregate final consumption, and

$X_t$  represents the level of electricity production by technology  $t$ .

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<sup>8</sup>Price rigidities such as fixed wages could be easily accommodated through the specification of explicit price constraints together with associated rationing conditions for the respective markets.

- Capital market clearance:

$$\bar{K} \geq \sum_i \frac{\partial \Pi_i^Y}{\partial p_K} Y_i + \sum_t \frac{\partial \Pi_t^{ELE}}{\partial p_K} X_t \quad (17)$$

- Market clearance for fossil fuel resources ( $i \in FF$ ):

$$\bar{Q}_i \geq \frac{\partial \Pi_i^Y}{\partial p_{Q,i}} Y_i \quad (18)$$

- Market clearance for capacity bounds:

$$\bar{U}_t \geq \frac{\partial \Pi_t^{ELE}}{\partial p_{U,t}} X_t \quad (19)$$

- Market clearance for production goods (except for electricity):

$$Y_i \geq \sum_j \frac{\partial \Pi_j^Y}{\partial p_i} Y_j + \sum_t \frac{\partial \Pi_t^{ELE}}{\partial p_i} X_t + \frac{\partial \Pi^C}{\partial p_i} C \quad (20)$$

- Market clearance for electricity:

$$\sum_t X_t \geq \sum_i \frac{\partial \Pi_i^Y}{\partial p_{ELE}} Y_i + \frac{\partial \Pi^C}{\partial p_{ELE}} C \quad (21)$$

- Market clearance for the final consumption composite:

$$C \geq \frac{M}{p_C} \quad (22)$$

Figure 1 provides a diagrammatic structure of our stylized economy using the notations of our algebraic exposition (for the sake of transparency, we do not consider the bottom-up representation of electricity generation here).

As to the parameterization of our simple numerical model, benchmark prices and quantities, together with exogenous elasticities, determine the free parameters of the functional forms that describe technologies and preferences. Table 1 describes our benchmark equilibrium in terms of a social accounting matrix (King [1985]).

Table 1: Base Year Equilibrium

	<i>ROI</i>	<i>COA</i>	<i>GAS</i>	<i>OIL</i>	<i>ELE</i>	<i>RA</i>	<i>Key</i>
<i>ROI</i>	200	-5	-5	-10	-180		<i>ROI</i> : rest of industry
<i>COA</i>		15			-15		<i>COA</i> : coal
<i>GAS</i>			15		-15		<i>GAS</i> : gas
<i>OIL</i>				30		-30	<i>OIL</i> : oil
<i>ELE</i>	-10				60	-50	<i>ELE</i> : electricity
Capital	-80				-20	100	<i>RA</i> : household
Labor	-110	-5	-5	-10		130	
Rent		-5	-5	-10		20	

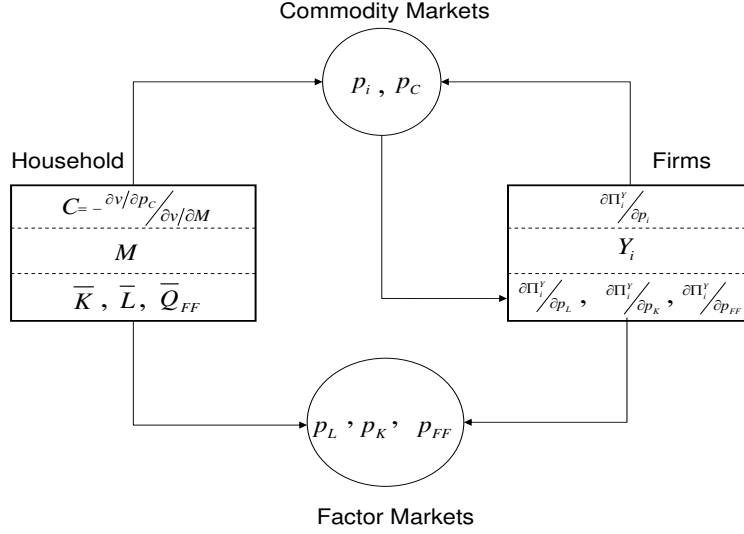


Figure 1: *Diagrammatic Structure of Stylized Economy*

In general, data consistency of a social accounting matrix requires that the sums of entries across each of the rows and columns equal zero: Market equilibrium conditions are associated with the rows, the columns capture the zero-profit condition for production sectors as well as the income balance for the aggregate household sector. Benchmark data are typically delivered in value terms, i.e. they are products of prices and quantities. In order to obtain separate price and quantity observations, the common procedure is to choose units for goods and factors so that they have a price of unity (net of potential taxes or subsidies) in the benchmark equilibrium. Then, the value terms simply correspond to the physical quantities.

Table 2 provides a bottom-up description of initially active power technologies (here: *gas*-fired power plants, *coal*-fired power plants, *nuclear* power plants, and *hydro* power plants) for the base year. Note that the benchmark outputs of active technologies sum up to economy-wide electricity demand while input requirements add up to aggregate demands as reported in the social accounting matrix.<sup>9</sup> Table 3 includes bottom-up technology coefficients (cost data) for initially inactive technologies (here: *wind*, *solar*, and *biomass*). In our example, unit-output of inactive technologies is listed as 10% more costly than the electricity price in the base year.<sup>10</sup>

<sup>9</sup>In our exposition, we impose consistency of aggregate top-down data with bottom-up technology data. In modelling practise, the harmonization of bottom-up data with top-down data may require substantial data adjustments to create a consistent database for the hybrid model.

<sup>10</sup>The cost gap for inactive technologies is an input that can be easily adjusted according to user assumptions within our numerical model implementation (see Appendix).

Table 2: Cost Structure of Active Technologies (Base Year)

	coal	gas	nuclear	hydro
<i>ELE</i>	20	20	12	8
<i>ROI</i>	-1	-1	-8	
<i>GAS</i>		-15		
<i>COA</i>	-15			
Capital	-4	-4	-4	-8

Table 3: Cost Structure of Inactive Technologies (Base Year)

	wind	solar	biomass
<i>ELE</i>	1	1	1
<i>ROI</i>	-0.2	-0.3	-0.4
Capital	-0.9	-0.8	-0.7
wind	-1		
sun		-1	
trees			-1

We can formulate the integrated top-down and bottom-up model as a system of weak inequalities and complementarity conditions based on the MCP approach. Appendix A provides a compact summary of the algebraic equilibrium conditions for our stylized hybrid model. The model is implemented in GAMS (Brooke et al. [1996]) using PATH (Dirkse and Ferris [1995]) as a solver. The programming files are attached in Appendix B – formulated either as an explicit MCP based on plain algebra or as an implicit MCP based on the meta-language MPSGE (Rutherford [1999a]).

## 4 Policy Simulations

In this section, we illustrate the use of our stylized hybrid bottom-up/top-down model for the economic assessment of three energy policy initiatives that figure prominently at the EU level: (i) nuclear phase-out, (ii) target quotas for renewables in electricity production (green quotas), and (iii) carbon taxation.

A central issue surrounding the controversial policy debate of these initiatives is the induced economic adjustment effects. Model-based simulation results of these effects may not only differ in the order of magnitude but even in the sign depending on the underlying parameterization and behavioral assumption. A concrete bottom-up representation of technological options may improve the "credibility" of model results. Furthermore, the MCP formulation of the hybrid bottom-up/top-down model permits representation of potentially important second-best effects that are typically omitted from market equilibrium models phrased as optimization problems.

In order to test the robustness of model results, sensitivity analysis with respect to uncertainties in the model's parameterization space is inevitable. A deliberate sensitivity analysis helps to identify robust insights on the complex relationships between assumptions (inputs) and results (outputs), i.e., to sort out the relative importance of a priori uncertainties. In this vein, our stylized model framework allows for user-defined changes of key model parameters.<sup>11</sup> Our results section below is restrained to the central case parameterization

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<sup>11</sup>The interested reader can use the GAMS program in the Appendix to perform sensitivity analysis.



and reports on selected economic dimensions such as welfare impacts (measured as Hicksian equivalent variation in income) or the composition of energy supply by technologies.

#### 4.1 Nuclear Phase-Out

Reservations against the use of nuclear power are reflected in policy initiatives of several EU Member States (Belgium, Germany, the Netherlands, Spain, and Sweden) that foresee a gradual phase-out of their nuclear power programs (OECD/IEA [2001]). In our stylized hybrid model, policy constraints on the use of nuclear power can be easily implemented via parametric changes of upper bounds (here:  $\bar{U}_{nuclear}$ ).

Figure 2 reports the welfare changes (vis-à-vis the benchmark level) as a function of the continuous reduction in nuclear power use. We report adjustment costs for two alternative assumptions on the relevant time horizon which are accommodated as a simple user-defined parametric switch in our model program: In the short-run analysis – labeled as “\_ short” – we assume that capital embodied in extant technologies is not malleable, whereas the long-run analysis – labeled as “\_ long” – presumes fully malleable (mobile) capital across all sectors and technologies. Obviously, adjustment costs to binding technological constraints are substantially higher in the short-run with restricted capital malleability (“stranded investment”).

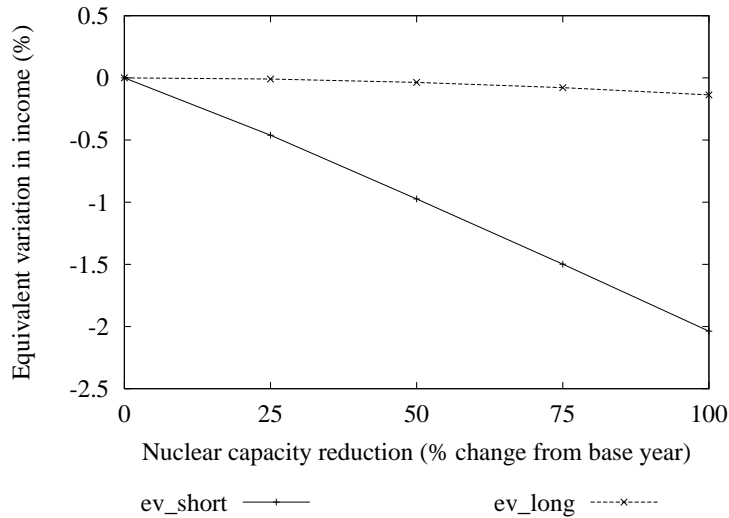


Figure 2: *Welfare Changes for Nuclear Phase-Out*

Figure 3 illustrates the changes in the supply of electricity across the different technologies in the long-run. For our illustrative cost parameterization of technologies, the administered decrease in nuclear power generation will be replaced by an increase in gas- and coal-based power generation whereas renewable technologies remain slack activities (apart from hydro

which is already operated at the upper bound in the reference situation).

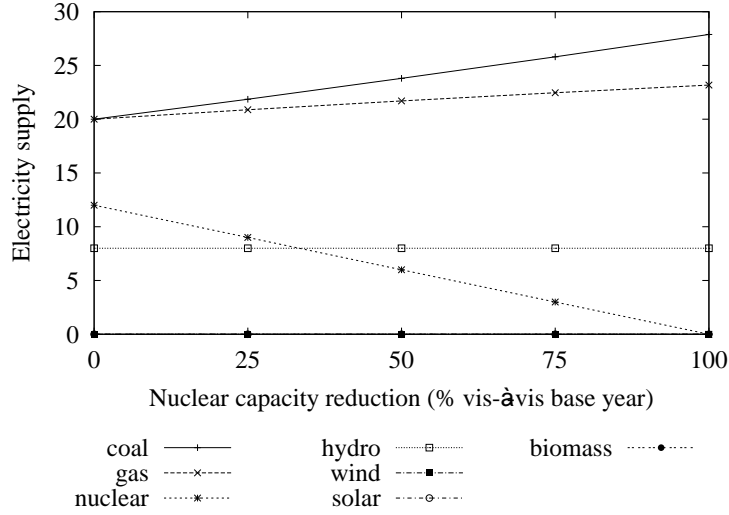


Figure 3: *Technology Shifts in Power Production for Nuclear Phase-Out*

## 4.2 Renewables Targets (Green Quotas)

Renewable energy technologies have received political support within the EU since the early 1970ies. After the oil crises renewable energy was primarily seen as a long-term substitution to fossil fuels in order to increase EU-wide security of supply. In the light of climate change, the motive has shifted to environmental concerns: Renewables are considered as an important alternative to thermal produced electricity that emits greenhouse gases. In 2001, the EU Commission issued a Directive which aims at doubling the share of renewable energy in EU-wide gross energy consumption 2010 as compared to 1997 levels (European Commission (EC) [2001]). In our stylized framework, we can implement the prescription of green quotas by setting a cumulative quantity constraint on the share of electricity that comes from renewable energy sources. This quantity constraint is associated with a complementary endogenous subsidy on renewable electricity production (paid by the representative household). The required changes to the algebraic model formulation include (i) the explicit quantity constraint on the target quota, (ii) endogenous subsidies on green electricity production, and (iii) the adjustment of the income constraint to account for overall subsidy payments (see Appendix). In our base year, the share of electricity produced by renewable energy sources (here: hydro) amounts to roughly 13%. In the counterfactual, we gradually increase this share to 33%. Figures 4 and 5 report the short-run and long-run implications for economic welfare and required subsidy rates.

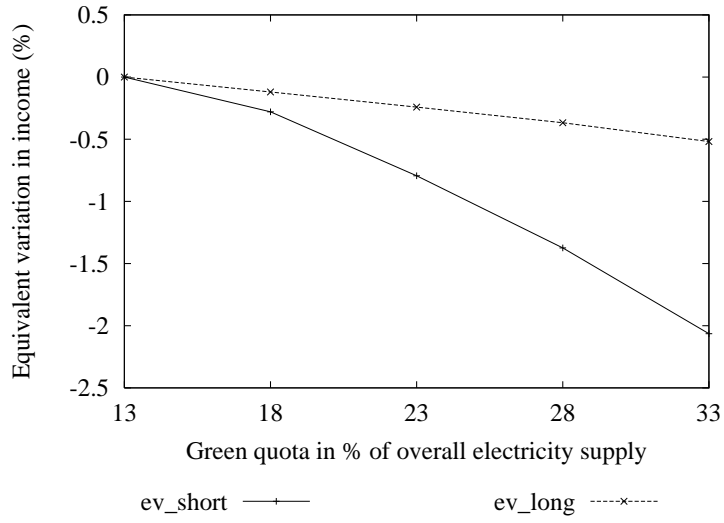


Figure 4: *Welfare Changes under Green Quotas*

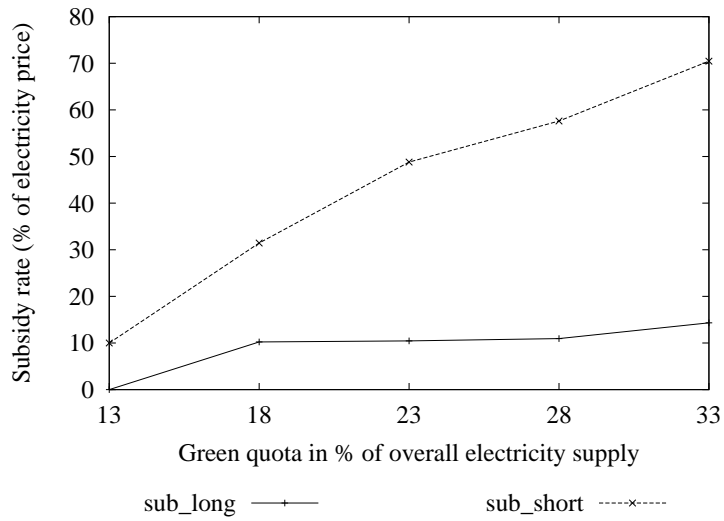


Figure 5: *Subsidy Rate for Green Quotas*

### 4.3 Carbon Taxation (Environmental Tax Reform)

Over the last decade, several EU Member States have levied some type of carbon tax in order to reduce greenhouse gas emissions from fossil fuel combustion that contribute to anthropogenic global warming (OECD [2001]). In this context, the debate on the double dividend

hypothesis has addressed the question of whether the usual trade-off between environmental benefits and gross economic costs<sup>12</sup> of emission taxes prevails in economies where distortionary taxes finance public spending. Emission taxes raise public revenues which can be used to reduce existing tax distortions. Revenue recycling may then provide prospects for a double dividend from emission taxation (Goulder [1995]): Apart from an improvement in environmental quality (the first dividend), the overall excess burden of the tax system may be reduced by using additional tax revenues for a revenue-neutral cut of existing distortionary taxes (the second dividend).<sup>13</sup>

Since our stylized hybrid model in MCP format is not limited by integrability constraints, we can use it to investigate the rationale behind the double dividend discussion. As a first step, we must refine Table 1 which so far only reports base year economic flows on a gross of tax basis in order to reflect some public finance information on initial taxes and public consumption. For the sake of simplicity, we assume that public demand amounts to some fixed share of base year *ROI* final consumption. The public consumption is financed by a distortionary consumption tax on *ROI*. In our policy simulations, we investigate the economic effects of carbon taxes that are set sufficiently high to reduce carbon emissions by 5%, 10%, 15%, and 20% compared to the base year emission level. While keeping the level of public good consumption at the base-year level, the additional carbon tax revenues can be either recycled lump-sum to the representative household or can be used to cut back distortionary capital taxes.

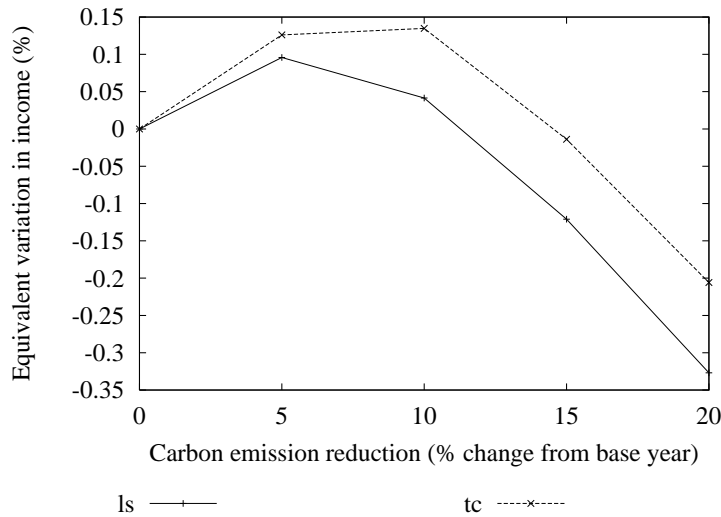


Figure 6: *Welfare Changes for Alternative Environmental Tax Reforms*

<sup>12</sup>That is the costs disregarding environmental benefits.

<sup>13</sup>If – at the margin – the excess burden of the environmental tax is smaller than that of the replaced (decreased) existing tax, public financing becomes more efficient and welfare gains will occur.

Figure 6 depicts the welfare implications of our environmental tax reforms. The first insight – in line with the undisputed weak-double dividend hypothesis (see Goulder 1995) – is that the reduction of the distortionary consumption tax is superior in efficiency terms as compared to a pure lump-sum recycling of carbon tax revenues. For modest environmental targets, we might even obtain a strong double-dividend from revenue-neutral cuts in the distortionary consumption tax. The second insight is less obvious and involves a bit more tricky second-best analysis: Even lump-sum recycling of carbon taxes may provide a strong double dividend when carbon reduction targets are set sufficiently low. The reasoning behind is that the initial consumption tax is only partially levied on non-energy consumption which distorts consumer choices in favor of energy (here: electricity) consumption. The imposition of carbon taxes counteracts to some level the initial distortions by the partial consumption tax as they lead to a relative price increase of primarily fossil-fuel based electricity.

## 5 Conclusions

There is a commonly perceived dichotomy between top-down CGE models and bottom-up energy system models dealing with energy issues. Bottom-up models provide a detailed description of the energy system from primary energy processing via multiple conversion, transport, and distribution processes to final energy use but neglect interactions with the rest of the economy. Furthermore, the formulation of such models as mathematical programs restricts their direct applicability to integrable equilibrium problems; many interesting policy problems involving initial inefficiencies can therefore not be handled – except for reverting to rather non-transparent sequential joint maximization techniques (Rutherford [1999b]). CGE models on the other hand are able to capture market interactions and inefficiencies in a comprehensive manner but typically lack technological details that might be relevant for the policy issue at hand.

In this paper, we have motivated the MCP approach to bridge the gap between bottom-up and top-down analysis. Through the explicit representation of weak inequalities and complementarity between decision variables and functional relationships, the MCP approach allows to exploit the advantages of each model type – technological details of bottom-up models and economic richness of top-down models – in a single mathematical format.

Despite the coherence and logical appeal of the integrated MCP approach, dimensionality may impose limitations on its practical application. Bottom-up programming models of the energy system often involve a large number of bounds on decision variables. These bounds are treated implicitly in the mathematical programming approach but introduce unavoidable complexity in the integrated complementarity formulation as they must be associated with explicit price variables in order to account for income effects. Therefore, future research may be dedicated to decomposition approaches that permit consistent combination of complex top-down models and large-scale bottom-up energy system models for energy policy analysis.

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## Appendix A: Algebraic Model Formulation

We can formulate the integrated top-down and bottom-up model as a system of weak inequalities and complementarity conditions based on the MCP approach. Table A1 provides the algebraic equilibrium conditions for our stylized hybrid model. The notations for variables and parameters employed within the algebraic exposition are explained in Tables A2 and A3.<sup>14</sup>

Table A1: Equilibrium Conditions

<i>Zero profit conditions</i>		
<ul style="list-style-type: none"> <li>Macro Production (<math>i \in ROI</math>):</li> </ul>	$\Pi_i^Y = p_i - \{(\theta_{L,i}p_L)^{1-\sigma} + (1 - \theta_{L,i})[\theta_{ELE,i}p_{ELE}^{1-\sigma_{ELE,i}} + (1 - \theta_{ELE,i})p_K^{1-\sigma_{ELE,i}}]^{\frac{1-\sigma}{1-\sigma_{ELE,i}}}\}^{\frac{1}{1-\sigma}}$	$\perp Y_i$
<ul style="list-style-type: none"> <li>Fossil Fuel Production (<math>i \in FF</math>):</li> </ul>	$\Pi_i^Y = p_i - \{\theta_i p_i^{1-\sigma_i} + (1 - \theta_i)[\theta_{ROI,i}p_{ROI} + (1 - \theta_{ROI,i})p_L]^{1-\sigma_i}\}^{\frac{1}{1-\sigma_i}}$	$\perp Y_i$
<ul style="list-style-type: none"> <li>Final Consumption:</li> </ul>	$\Pi^C = p_C - \{\theta_{ROI,C}p_{ROI}^{1-\sigma_C} + (1 - \theta_{ROI,C})[\theta_{ELE,C}p_{ELE}^{1-\sigma_{ELE,C}} + (1 - \theta_{ELE,C})p_{OIL}^{1-\sigma_{ELE,C}}]^{\frac{1-\sigma_C}{1-\sigma_{ELE,C}}}\}^{\frac{1}{1-\sigma_C}}$	$\perp C$
<ul style="list-style-type: none"> <li>Electricity production by technology (<math>t</math>):</li> </ul>	$\Pi_t^{ELE} = p_{ELE} - \theta_{ROI,t}p_{ROI} - \theta_{K,t}p_K - \sum_{(i \in FF)} \theta_{FF,t}p_{FF} - p_{U,t}$	$\perp X_t$
<i>Market clearance conditions</i>		
<ul style="list-style-type: none"> <li>Labor:</li> </ul>	$\bar{L} \geq \sum_i \frac{\partial \Pi_i^Y}{\partial p_L} Y_i + \sum_t \frac{\partial \Pi_t^{ELE}}{\partial p_L} X_t$	$\perp p_L$
<ul style="list-style-type: none"> <li>Capital:</li> </ul>	$\bar{K} \geq \sum_i \frac{\partial \Pi_i^Y}{\partial p_K} Y_i + \sum_t \frac{\partial \Pi_t^{ELE}}{\partial p_K} X_t$	$\perp p_K$
<ul style="list-style-type: none"> <li>Fossil fuel resources (<math>i \in FF</math>):</li> </ul>	$\bar{Q}_i \geq \frac{\partial \Pi_i^Y}{\partial p_{Q,i}} Y_i$	$\perp P_{Q,i}$
<ul style="list-style-type: none"> <li>Capacity constraints (<math>i \in FF</math>):</li> </ul>	$\bar{U}_t \geq \frac{\partial \Pi_t^{ELE}}{\partial p_{U,t}} X_t$	$\perp p_{U,t}$
<ul style="list-style-type: none"> <li>Production goods except for electricity:</li> </ul>		

<sup>14</sup>We use the " $\perp$ " operator to indicate complementarity between equilibrium conditions and the respective decision variables.



$Y_i \geq \sum_j \frac{\partial \Pi_j^Y}{\partial p_i} Y_j + \sum_t \frac{\partial \Pi_t^{ELE}}{\partial p_i} X_t + \frac{\partial \Pi^C}{\partial p_i} C$	$\perp p_i$
<ul style="list-style-type: none"> <li>Electricity:</li> </ul> $\sum_t X_t \geq \sum_i \frac{\partial \Pi_i^Y}{\partial p_{ELE}} Y_i + \frac{\partial \Pi^C}{\partial p_{ELE}} C$	$\perp p_{ELE}$
<ul style="list-style-type: none"> <li>Final consumption composite:</li> </ul> $C \geq \frac{M}{p_C}$	$\perp p_C$
<i>Income balance</i>	
$M = p_L \bar{L} + p_K \bar{K} + \sum_{i \in FF} p_{Q,i} \bar{Q}_i + \sum_t \bar{U}_t p_{U,t}$	$\perp M$

Table A2: Variables

<i>Activity variables</i>	
$Y_i$	Production of good $i$ (except for electricity)
$C$	Aggregate final consumption
$X_t$	Production of electricity by technology $t$
<i>Price variables</i>	
$p_i$	Price of good $i$
$p_L$	Wage rate
$p_K$	Price of capital
$p_{U,t}$	Shadow price on capacity upper bound for technology $t$
$p_{Q,i}$	Scarcity price of fossil fuel resources ( $i \in FF$ )
$p_C$	Price of the final consumption composite
<i>Income variables</i>	
$M$	Income of representative household

Table A3: Cost Shares, Elasticities, and Endowments

<i>Cost shares</i>	
$\theta_{L,i}$	Cost share of labor in production of good $i$ (except for electricity)
$\theta_{ELE,i}$	Cost share of electricity in sector-specific capital-electricity composite ( $i \in ROI$ )
$\theta_i$	Cost share of fossil fuel resource in fossil fuel production ( $i \in FF$ )
$\theta_{ROI,i}$	Cost share of $ROI$ in $ROI$ -labor composite of fossil fuel production ( $i \in FF$ )
$\theta_{ROI,C}$	Cost share of $ROI$ in final consumption
$\theta_{ELE,C}$	Cost share of electricity in oil-electricity composite of final consumption
$\theta_{ROI,t}$	Cost share of $ROI$ in electricity production by technology $t$
$\theta_{K,t}$	Cost share of capital in electricity production by technology $t$
$\theta_{FF,t}$	Cost share of fossil fuel $FF$ in electricity production by technology $t$
<i>Elasticities of substitution</i>	
$\sigma$	Elasticity of substitution between labor and non-labor inputs in production of good $i$ ( $i \in ROI$ )
$\sigma_{ELE,i}$	Elasticity of substitution between electricity and capital in production of good $i$ ( $i \in ROI$ )
$\sigma_i$	Elasticity of substitution between resource input and non-resource inputs in production of fossil fuels ( $i \in FF$ )
$\sigma_C$	Elasticity of substitution between energy and non-energy inputs in final consumption
$\sigma_{ELE,C}$	Elasticity of substitution between electricity and oil in final consumption
<i>Endowments</i>	
$\bar{L}$	Aggregate labor endowment
$\bar{K}$	Aggregate capital endowment
$\bar{Q}_{FF}$	Resource endowment with fossil fuel $FF$
$\bar{U}_t$	Capacity of technology $t$

## Appendix B: GAMS Programs

### 5.1 MCP Formulation

```
1 $Title  Static maquette of integrated TD/BU hybrid model
2
3 *      Model formulation in MCP
4
5 *=====
6 * Model code for stylzed integrated bottom-up/top-down analysis of energy
7 * policies based on:
8 *
9 *      ZEW Discussion Paper 05-28
10 *      Integrating Bottom-Up into Top-Down:
11 *      A Mixed Complementarity Approach
12 *
13 * Contact the authors at: boehringer@zew.de; rutherford@colorado.edu
14 *=====
15
16 * For plotting the results you must have installed the gnuplot-shareware
17 * (see http://debreu.colorado.edu/gnuplot/gnuplot.htm for downloads)
18
19 *=====
20 *      List of parameters subject to sensitivity analysis
21 *      The user can change the default settings.
22
23 * Choice of key elasticities:
24 *      Elasticity of substitution in final consumption
25 $if not setglobal esub_c $setglobal esub_c 0.5
26
27 *      Elasticity in gas supply
28 $if not setglobal esub_gas $setglobal esub_gas 1.5
29
30 *      Elasticity in coal supply
31 $if not setglobal esub_coal $setglobal esub_coal 3
32
33 *      Elasticity in oil supply
34 $if not setglobal esub_oil $setglobal esub_oil 1.5
35
36
37 * Choice of resource availability for renewables:
38 * (as a fraction of base-year total electricity production)
39 *      Potential wind supply - (%)
```

```

40 $if not setglobal p_wind $setglobal p_wind 10
41
42 *      Potential solar supply - (%)
43 $if not setglobal p_sun $setglobal p_sun 10
44
45 *      Potential biomass supply - (%)
46 $if not setglobal p_trees $setglobal p_trees 10
47
48
49 * Cost disadvantage of initial slack technologies:
50 *      Wind energy premium (%)
51 $if not setglobal c_wind $setglobal c_wind 10
52
53 *      Solar energy premium (%)
54 $if not setglobal c_solar $setglobal c_solar 10
55
56 *      Biomass energy premium (%)
57 $if not setglobal c_biomass $setglobal c_biomass 10
58
59
60 * Other central model assumptions:
61 *      Time horizon (short, long)
62 *      N.B.: For short-run analysis capital is immobile across sectors
63 $if not setglobal horizon $setglobal horizon long
64
65 *=====
66
67
68 *      Assign user-specific changes of default assumptions
69 scalar  shortrun      Flag for short-run capital mobility/1/;
70
71 $if "%horizon%"=="long" shortrun=0;
72
73 *      Elasticities of substitution (ESUB)
74 scalar  esub_c      Elasticity of substitution in final demand /%esub_c%/
75          esub_ele    ESUB between electricity and oil in final demand /0.5/
76          esub_k_e    ESUB between capital and energy in ROI production /0.5/
77          esub_l_ke   ESUB between labor and other inputs in ROI production /0.8/;
78
79 set     t            Electricity Technologies (current and future)
80          /coal,gas,nuclear,hydro,wind,solar,biomass/;
81
82 set     xt(t)        Existing technologies /coal,gas,nuclear,hydro/;

```

```

83
84 set      nt(t)    New vintage technologies /wind,solar,biomass/;
85
86 set      ff       Fossil fuel inputs /coa, gas, oil/;
87
88 set      n        Natural resources /wind, sun, trees/;
89
90
91 set      res(t)   Renewable energy sources /hydro, wind, solar, biomass/;
92
93 *        The following data table describes an economic equilibrium in
94 *        the base year:
95
96
97 table sam  Base year social accounting matrix
98
99          roi      coa      gas      oil      ele      ra
100 roi      200      -5       -5       -10      -10     -170
101 coa              15              -15
102 gas              15              -15
103 oil              30              -30
104 ele      -10              60      -50
105 capital -80              -20      100
106 labor    -110     -5       -5       -10              130
107 rent              -5       -5       -10              20          ;
108
109 parameter carbon(ff)  Carbon coefficients /oil 1, gas 1, coa 2/;
110
111 scalar  carblim        Carbon target /0/;
112
113 parameter  esub_ff(ff) Elasticity of substitution in fossil fuel production
114            /gas %esub_gas%, coa %esub_coal%, oil %esub_oil%/;
115
116 *        The following data tables describes electricity generation in
117 *        the base year as well as the technology coefficients for technologies
118 *        which are inactive in the base year (wind, solar, biomass). Inactive
119 *        technologies are by defaults %c_****% more costly.
120
121 table xtelec  Electricity technologies - extant (initially active)
122
123          coal      gas      nuclear hydro
124 ele      20       20          12      8
125 roi      -1       -1          -8

```

```

126 gas          -15
127 coa          -15
128 capital      -4      -4      -4      -8;
129
130
131 table ntelec  Electricity technologies - new vintage (initially inactive)
132
133          wind      solar      biomass
134 ele        1.0      1.0      1.0
135 roi        -.2      -.3      -.4
136 capital     -.9      -.8      -.7
137 wind       -1.0
138 sun                -1.0
139 trees                -1.0;
140
141
142 *          Adjust the cost coefficients for initially inactive technologies
143 *          according to user assumptions:
144 set xk /roi, capital/;
145
146 ntelec(xk,"wind")    = ntelec(xk,"wind")    * (100+%c_wind%)/110;
147 ntelec(xk,"solar")   = ntelec(xk,"solar")   * (100+%c_solar%)/110;
148 ntelec(xk,"biomass") = ntelec(xk,"biomass") * (100+%c_biomass%)/110;
149
150
151 *          Specify limits (resource or policy constraints) to the availability
152 *          of technologies
153
154 parameter limit      Electricity supply limits on extant technologies /
155          nuclear      12
156          hydro        8 /;
157
158 parameter nrsupply(n) Natural resource supplies (fraction of base output)/
159          wind          %p_wind%
160          sun           %p_sun%
161          trees         %p_trees% /;
162
163 nrsupply(n) = nrsupply(n)/100 * sam("ele","ele");
164
165 parameter c0      Baseyear final consumption;
166 c0 = (-sam("roi","ra")-sam("ele","ra")-sam("oil","ra"));
167
168

```

```

169 set      quota(t)  Flag for technologies contributing to green quota;
170 quota(t) = no;
171
172 scalar  share      Target share for green quota /0/;
173
174 *          By default we might set target share for green quota at base year level
175 share = sum(t$res(t), xtelec("ele",t))/sum(t, xtelec("ele",t));
176 display share;
177
178 scalar
179      dd      Flag for double dividend policy analysis /0/,
180      ls      Flag for lump-sum revenue-recycling      /0/,
181      vat      Flag for VAT revenue recycling          /0/,
182      g0      Base year public consumption            /0/,
183      tc0     Base year consumption tax                /0/;
184
185
186 positive variables
187 *          Activitiy levels
188 roi        Aggregate output
189 ele(t)     Production levels for electricity by technology
190 s(ff)      Fossil fuel supplies
191 c          Aggregate consumption (utility) formation
192 g          Public good provision
193
194 *          Price levels
195 proi       Price of aggregate output
196 pele       Price of electricity
197 pf(ff)     Price of oil and gas
198 pl        Wage rate
199 pk        Price of malleable capital for X (and NT elec)
200 pr(ff)     Rent on fossil fuel resources
201 pn(n)      Rent on natural resources
202 pc        Consumption (utility) price index
203 pg        Price of public consumption
204 plim(t)    Shadow price on electricity expansion
205 pkx(t)     Price of capital to extant technologies
206 pcarb     Carbon tax rate
207
208 *          Income variables
209 ra        Representative household
210 govt      Government
211

```

212 \*           Endogenous taxes or subsidies  
 213 tau        Uniform subsidy rate on renewable energy;  
 214  
 215 positive variables  
 216 phi\_ls   Lump-sum recycling  
 217 phi\_tc   Consumption tax recycling;  
 218  
 219  
 220 equations  
 221  
 222 \*           Zero profit conditions for activities linked to activity levels  
 223 zprf\_roi       Zero profit condition for macro production sector  
 224 zprf\_ele(t)   Zero profit condition for alternative electricity supply technologies  
 225 zprf\_s(ff)    Zero profit condition for fossil fuel supplies  
 226 zprf\_c        Zero profit condition for aggregate utility formation  
 227 zprf\_g        Zero profit condition for public good formation  
 228  
 229 \*           Market clearance conditions for goods linked to prices  
 230 mkt\_proi       Market clearance condition for macro production good  
 231 mkt\_pele       Market clearance condition for electricity  
 232 mkt\_pf(ff)    Market clearance condition for fossil fuels coal and gas  
 233 mkt\_pl        Market clearance condition for labor  
 234 mkt\_pk        Market clearance condition for malleable capital  
 235 mkt\_pr(ff)    Market clearance conditions for fossil fuel resources  
 236 mkt\_pn(n)     Market clearance conditions for natural resources  
 237 mkt\_pcarb     Market clearance condition for carbon  
 238 mkt\_pkx(t)    Market clearance condition for capital inputs to extant power production  
 239 mkt\_plim(t)   Market clearance condition for capacity on electricity expansion  
 240 mkt\_pc        Market clearance for aggregate utility good  
 241 mkt\_g         Market clearance for public good  
 242  
 243 \*           Income balance for representative household linked to income level  
 244 inc\_ra        Budget constraint for representative household  
 245 inc\_govt      Budget constraint for government  
 246  
 247 \*           Additional constraints  
 248 sub\_res       Endogenous subsidy to achieve renewable energy quota  
 249 eqy\_ls        Equal yield constraint for lump-sum recycling  
 250 eqy\_tc        Equal yield constraint for consumption tax recycling  
 251  
 252 parameter  
 253 theta\_l\_roi    Cost share of labor in ROI production  
 254 theta\_ele\_roi   Cost share of electricity in capital-electricity composite of ROI



```

255 theta_r_ff(ff)    Cost share of fossil fuel resource in fossil fuel production
256 theta_l_ff(ff)    Cost share of labor in non-resource input of fossil fuel production
257 theta_roi_ff(ff)  Cost share of ROI in ROI-labor composite of fossil fuel production
258 theta_ele_c       Cost share of electricity in oil-electricity composite of final consmption
259 theta_roi_c       Cost share of ROI in final consumption
260 theta_roi_t(t)    Cost share of ROI in electricity production by technology t
261 theta_k_t(t)      Cost share of capital in electricity production by technology t
262 theta_ff_t(ff,t)  Cost share of fossil fuel in electricity production by technology t;
263
264 theta_roi_c       = -sam("roi","ra")/c0;
265 theta_l_roi       = (-sam("labor","roi"))/sam("roi","roi");
266 theta_ele_roi     = (-sam("ele","roi"))/ ((-sam("capital","roi")) + (-sam("ele","roi")));
267 theta_r_ff(ff)    = (-sam("rent",ff))/ ((-sam("rent",ff)) + (-sam("roi",ff)) + (-sam("labor",ff)));
268 theta_roi_ff(ff)= (-sam("roi",ff)) / ((-sam("roi",ff)) + (-sam("labor",ff)));
269 theta_ele_c       = (-sam("ele","ra"))/((-sam("ele","ra")) + (-sam("oil","ra")));
270 theta_roi_t(t)$xt(t) = (-xtelec("roi",t)/xtelec("ele",t));
271 theta_k_t(t)$xt(t)   = (-xtelec("capital",t)/xtelec("ele",t));
272 theta_ff_t(ff,t)$xt(t) = (-xtelec(ff,t)/xtelec("ele",t));
273 theta_roi_t(t)$nt(t) = (-ntelec("roi",t)/ntelec("ele",t));
274 theta_k_t(t)$nt(t)   = (-ntelec("capital",t)/ntelec("ele",t));
275 theta_l_ff(ff)      = (-sam("labor",ff))/((-sam("labor",ff))+(-sam("roi",ff)));
276
277 *      Definition of zero profit conditions
278 zprf_roi..
279     (theta_l_roi*pl**(1-esub_l_ke) + (1- theta_l_roi)
280     *(theta_ele_roi*pele**(1-esub_k_e) + (1-theta_ele_roi)*pk**(1-esub_k_e))
281     **((1-esub_l_ke)/(1-esub_k_e)))*(1/(1-esub_l_ke))
282     =G= proi;
283
284 zprf_ele(t)..
285     {theta_roi_t(t)*proi+ sum(ff,theta_ff_t(ff,t)*pf(ff))
286     + (theta_k_t(t)*pkx(t))$shortrun
287     + (theta_k_t(t)*pk)$ (not shortrun)
288     + plim(t)$limit(t)
289     }$xt(t)
290     +
291     {theta_roi_t(t)*proi + theta_k_t(t)*pk + sum(n, (-ntelec(n,t))*pn(n))}$nt(t)
292     =G= pele*(1+tau$quota(t));
293
294 zprf_s(ff)..
295     (theta_r_ff(ff)*pr(ff)**(1-esub_ff(ff)) + (1-theta_r_ff(ff))*( theta_l_ff(ff)*pl
296     + (1-theta_l_ff(ff))*proi)**(1-esub_ff(ff)))*(1/(1-esub_ff(ff)))
297     + ((carbon(ff)*pcarb))$carblim

```

```

298         =G= pf(ff);
299
300 zprf_c..
301     (theta_roi_c*((proi*(1+tc0*phi_tc$dd))/(1+tc0$dd))*(1-esub_c)
302     + (1-theta_roi_c)*(theta_ele_c*pele**(1-esub_ele)
303     +(1-theta_ele_c)*pf("oil")**(1-esub_ele))*((1-esub_c)/(1-esub_ele)))*(1/(1-esub_c))
304     =G= pc;
305
306 zprf_g$dd..
307     proi =G= pg;
308
309 *      Definition of market clearance conditions
310 mkt_proi..
311     roi=sam("roi","roi") =G=
312     sum(xt, ele(xt)*(-xtelec("roi",xt)/xtelec("ele",xt)))
313     + sum(nt, ele(nt)*(-ntelec("roi",nt)))
314     + sum(ff, (-sam("roi",ff))*s(ff)* ((theta_r_ff(ff)*pr(ff)**(1-esub_ff(ff))
315     + (1-theta_r_ff(ff))*( theta_l_ff(ff)*pl
316     + (1-theta_l_ff(ff))*proi)**(1-esub_ff(ff)))*(1/(1-esub_ff(ff)))
317     /( theta_l_ff(ff)*pl + (1-theta_l_ff(ff))*proi)**esub_ff(ff))
318     + (-sam("roi","ra")/(1+tc0$dd))*c*( pc/(proi*(1+(tc0*phi_tc)$dd))*(1+tc0$dd)**esub_c
319     + (g0*g)$dd;
320
321 mkt_pele..
322     sum(t, ele(t)) =G=
323     (-sam("ele","ra"))*c*(pc/(theta_ele_c*pele**(1-esub_ele)
324     +(1-theta_ele_c)*pf("oil")**(1-esub_ele))*(1/(1-esub_ele)))*esub_c
325     * (((theta_ele_c*pele**(1-esub_ele)
326     +(1-theta_ele_c)*pf("oil")**(1-esub_ele))*(1/(1-esub_ele)))/pele)**esub_ele
327     + (-sam("ele","roi"))*roi*(proi/((theta_ele_roi*pele**(1-esub_k_e)
328     + (1-theta_ele_roi)*pk**(1-esub_k_e))*(1/(1-esub_k_e))))**esub_l_ke
329     *((theta_ele_roi*pele**(1-esub_k_e)
330     + (1-theta_ele_roi)*pk**(1-esub_k_e))*(1/(1-esub_k_e))/pele)**esub_k_e;
331
332 mkt_pf(ff)..
333     sam(ff,ff)*s(ff) =G=
334     sum(xt, (-xtelec(ff,xt)/xtelec("ele",xt))*ele(xt))
335     + (-sam(ff,"ra"))*c*(pc/(theta_ele_c*pele**(1-esub_ele)
336     +(1-theta_ele_c)*pf("oil")**(1-esub_ele))*(1/(1-esub_ele)))*esub_c
337     * (((theta_ele_c*pele**(1-esub_ele)
338     +(1-theta_ele_c)*pf("oil")**(1-esub_ele))*(1/(1-esub_ele)))/pf("oil"))**esub_ele;
339
340 mkt_pl..

```

```

341      sam("labor","ra") =G=
342      (-sam("labor","roi"))*roi*(proi/pl)**esub_l_ke
343      + sum(ff, (-sam("labor",ff))*s(ff)* ((theta_r_ff(ff)*pr(ff)**(1-esub_ff(ff))
344      + (1-theta_r_ff(ff))*( theta_l_ff(ff)*pl
345      + (1-theta_l_ff(ff))*proi)**(1-esub_ff(ff)))*(1/(1-esub_ff(ff)))
346      /( theta_l_ff(ff)*pl + (1-theta_l_ff(ff))*proi)**esub_ff(ff));
347
348 mkt_pk..
349      (-sam("capital","roi")+sum(xt,(-xtelec("capital",xt)))$(not shortrun)) =G=
350      (-sam("capital","roi"))*roi*(proi/((theta_ele_roi*pele**(1-esub_k_e)
351      + (1-theta_ele_roi)*pk**(1-esub_k_e)**(1/(1-esub_k_e))))**esub_l_ke
352      *((theta_ele_roi*pele**(1-esub_k_e)
353      + (1-theta_ele_roi)*pk**(1-esub_k_e)**(1/(1-esub_k_e)))/pk)**esub_k_e
354      + sum(xt$(not shortrun),(-xtelec("capital",xt)/xtelec("ele",xt))*ele(xt))
355      + sum(nt,(-ntelec("capital",nt))*ele(nt));
356
357 mkt_pr(ff)..
358      (-sam("rent",ff)) =G=
359      (-sam("rent",ff))*s(ff)* ((theta_r_ff(ff)*pr(ff)**(1-esub_ff(ff))
360      + (1-theta_r_ff(ff))*( theta_l_ff(ff)*pl
361      + (1-theta_l_ff(ff))*proi)**(1-esub_ff(ff)))*(1/(1-esub_ff(ff)))/pr(ff)** esub_ff(ff);
362
363 mkt_pn(n)..
364      nrsupply(n) =G= sum(nt,(-ntelec(n,nt))*ele(nt));
365
366 mkt_pkx(xt)$shortrun..
367      (-xtelec("capital",xt)) =G= (-xtelec("capital",xt)/xtelec("ele",xt))*ele(xt);
368
369 mkt_plim(xt)$limit(xt)..
370      limit(xt) =G= ele(xt);
371
372 mkt_pcarb$carblim..
373      carblim =G= sum(ff,(carbon(ff)*sam(ff,ff))*s(ff));
374
375 mkt_pc ..
376      c0*c =G= ra/pc ;
377
378 mkt_g$dd ..
379      g0*g =G= govt/pg ;
380
381 *      Income definition for representative household
382 inc_ra..
383      (-sam("capital","roi")+sum(xt,(-xtelec("capital",xt)))$(not shortrun))*pk

```

```

384 + sum(xt$shortrun, (-xtelec("capital",xt))*pkx(xt))
385 + sam("labor","ra")*pl
386 + sum(ff,(-sam("rent",ff))*pr(ff))
387 + sum(n, nrsupply(n)*pn(n))
388 + (carblim*pcarb)$carblim$(not dd)
389 + sum(xt$limit(xt), limit(xt)*plim(xt))
390 - sum(t$quota(t), pele*ele(t)*tau)
391 - (pc*phi_ls)$dd
392 =G= ra;
393
394 *      Income definition for government
395 inc_govt$dd..
396 (carblim*pcarb)$carblim + pc*phi_ls
397 + ((-sam("roi","ra")/(1+tc0$dd))*c
398 *( (pc/(proi*(1+(tc0*phi_tc)$dd)))*(1+tc0$dd)**esub_c)*proi*tc0*phi_tc
399 =G= govt;
400
401 *      Endogenous subsidy to assure renewables quota
402 sub_res$card(quota)..
403 sum(t$res(t), ele(t)) =G= share*sum(t, ele(t));
404
405 *      Endogenous equal yield constraints
406 eqy_ls$dd..
407 g =G= 1;
408
409 eqy_tc$dd..
410 g =G= 1;
411
412
413 *      Define MCP model
414 model mcp_hybrid / zprf_roi.roi, zprf_ele.ele, zprf_s.s, zprf_c.c, zprf_g.g,
415 mkt_proi.proi, mkt_pele.pele, mkt_pf.pf, mkt_pl.pl,
416 mkt_pk.pk, mkt_pr.pr, mkt_pn.pn, mkt_pcarb.pcarb,
417 mkt_pkx.pkx, mkt_plim.plim, mkt_pc.pc, mkt_g.pg, inc_ra.ra,
418 sub_res.tau, inc_govt.govt, eqy_ls.phi_ls, eqy_tc.phi_tc
419 /;
420
421 *      Benchmark initialization
422
423 *      In the base year new-vintage technologies are inactive
424 *      and the prices of backstop natural resources are zero
425 *      Extant technologies with capacity limits are assumed to
426 *      operate at the upper bound with a zero shadow value in the

```

```

427 *      base year
428
429 ele.l(nt) = 0;
430 pn.l(n) = 0;
431 plim.l(xt) = 0;
432
433 ele.l(xt) = xtelec("ele",xt);
434
435 *      Initialize activities and prices
436 roi.l = 1; ele.l(xt)= xtelec("ele",xt); s.l(ff) = 1; c.l = 1;
437 proi.l = 1; pele.l = 1; pf.l(ff) = 1; pl.l = 1; pk.l = 1; pr.l(ff) = 1;
438 pkx.l(t)$((-xtelec("capital",t))$shortrun) = 1; plim.l(t) = 0;
439 pn.l(n) = 1; pc.l = 1;
440
441 *      Install lower bounds on prices to avoid division by zero in MCP formulation
442 proi.lo = 1e-5; pele.lo = 1e-5; pf.lo(ff) = 1e-5; pl.lo = 1e-5; pk.lo = 1e-5;
443 pr.lo(ff) = 1e-5; pkx.lo(t)$((-xtelec("capital",t))$shortrun) = 1e-5; pc.lo = 1e-5;
444
445 *      Tie down "active" model specification
446 phi_tc.fx = 1; phi_ls.fx = 0;
447 g.fx = 0; pg.fx = 0; govt.fx = 0; pcarb.fx = 0;
448 pkx.fx(t)$ (not (-xtelec("capital",t))$shortrun) = 0;
449 tau.fx$ (not card(quota)) = 0;
450 plim.fx(t)$ (not limit(t)) = 0;
451
452 *      In the base year we have no new-vintage electricity and the prices of backstop
453 *      natural resources are zero:
454
455 ele.l(nt) = 0;
456 pn.l(n) = 0;
457 pcarb.l = 0;
458 pkx.l(t)$((-xtelec("capital",t))$shortrun) = 1;
459
460 ra.l = (-sam("capital","roi")+sum(xt,(-xtelec("capital",xt))$ (not shortrun))*pk.l
461         + sum(xt$shortrun, (-xtelec("capital",xt))*pkx.l(xt))
462         + sam("labor","ra")*pl.l
463         + sum(ff,(-sam("rent",ff))*pr.l(ff))
464         + sum(n, nrsupply(n)*pn.l(n))
465         + (carblim*pcarb.l)$carblim
466         + sum(xt$limit(xt), limit(xt)*plim.l(xt))
467         - sum(t$quota(t), pele.l*ele.l(t)*tau.l)
468         - (pc.l*phi_ls.l)$dd;
469

```

```

470 govt.l$dd = (carblim*pcarb.l)$carblim + pc.l*phi_ls.l
471             + (-sam("roi","ra")/(1+tc0$dd))*c.l*(pc.l/(proi.l*(1+tc0*phi_tc.l)$dd)
472             /(1+tc0$dd))*esub_c*pc.l*tc0*phi_tc.l;
473
474 *      Check the benchmark:
475 *      - marginal of all active activities must be zero
476 *      - marginal of all positive prices must be zero
477 *      - marginal of all positive incomes must be zero
478
479 mcp_hybrid.iterlim = 0;
480 solve mcp_hybrid using mcp;
481
482 *      Relax iteration limit for counterfactual policy analysis
483 mcp_hybrid.iterlim      = 4000;
484
485 *=====
486 *      Analysis of policy scenarios (as laid out in the paper)
487 *
488 *      (i)   gradual nuclear phase-out
489 *      (ii)  target quota for renewables (green quota)
490 *      (iii) carbon taxation (environmental tax reform)
491
492
493 *      Define report parameters
494 parameter
495     ev(*)           Equivalent variation in income
496     supply(*,*)     Electricity supply by technology
497     carbtax(*)       Carbon permit price
498     subsidy          Subsidy rate on electricity from renewables
499     report           Report default parameter;
500
501 scalar epsilon /1.e-5/;
502
503 *=====
504 *      Scenario 1: Gradual nuclear phase-out
505
506 set      nsc  Nuclear phase scenarios / 0, 25, 50, 75, 100/;
507
508 parameter limit_0      Base year capacity limits;
509 limit_0("nuclear") = limit("nuclear");
510
511 loop(nsc,
512

```

```

513 *      Assign available capacity for nuclear power
514      limit("nuclear") = (1 - (ord(nsc)-1)/(card(nsc)-1))*limit_0("nuclear");
515 Display limit;
516 *      If nuclear capacity is set to zero, assure complete nuclear phase out
517      if ((not limit("nuclear")),
518          ele.fx("nuclear") = 0;
519      );
520      solve mcp_hybrid using mcp;
521      supply(nsc,t)      = ele.l(t)  + epsilon;
522      ev(nsc)            = 100 * (c.l-1) + epsilon ;
523
524 );
525
526
527 $setglobal labels nsc
528 $setglobal gp_opt0 "set data style linespoints"
529
530 $setglobal gp_opt1 "set key below"
531 report(nsc,"ev") = ev(nsc);
532 $setglobal gp_opt2 "set title 'Welfare changes'"
533 $setglobal gp_opt3 "set xlabel 'Nuclear capacity reduction (% vis--vis BaU)'"
534 $setglobal gp_opt4 "set ylabel 'Equivalent variation in income (%)'"
535 $libinclude plot report
536 display report;
537 report(nsc,"ev") = 0;
538
539 $setglobal gp_opt2 "set title 'Electricity supply by technology'"
540 $setglobal gp_opt3 "set xlabel 'Nuclear capacity reduction (% vis--vis BaU)'"
541 $setglobal gp_opt4 "set ylabel 'Activity level of technologies'"
542 $libinclude plot supply
543
544 *      Re-initialize parameterization for subsequent scenarios
545 limit("nuclear") = limit_0("nuclear");
546 ele.lo("nuclear") = 0; ele.up("nuclear") = +inf; ele.l("nuclear")=xtelec("ele","nuclear");
547
548
549 *=====
550 *      Scenario 2: Green quotas
551
552 set      qsc  Green quota scenarios / 0 13, 5 18, 10 23, 15 28, 20 33/;
553 *      Note:   We start from the base year situation without binding target
554 *              share and then increase the share iteratively by 5%.
555 *              The descriptive text for scenario set elements captures

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```

556 *           the actual target level of green electricity as percent
557 *           in overall electricity production (base year quota is 13%).
558 *           The plot-command picks up the descriptive text as
559 *           scenario labels when produce a graphical exposition of results.
560
561 *           Assign initial level values for variables
562 roi.l = 1; ele.l(xt)= xtelec("ele",xt);  s.l(ff) = 1; c.l = 1;
563 proi.l = 1; pele.l = 1; pf.l(ff) = 1; pl.l = 1; pk.l = 1; pr.l(ff) = 1;
564 pkx.l(t)$((-xtelec("capital",t))$shortrun) = 1; plim.l(t) = 0;
565 pn.l(n) = 1; pc.l = 1;
566 *           Install lower bounds on prices to avoid division by zero in MCP formulation
567 proi.lo = 1e-5; pele.lo = 1e-5; pf.lo(ff) = 1e-5; pl.lo = 1e-5; pk.lo = 1e-5; pr.lo(ff) = 1e-5;
568 pkx.lo(t)$((-xtelec("capital",t))$shortrun) = 1e-5; pc.lo = 1e-5;
569 ra.l = c0;
570
571 parameter share_0      Base year renewable share;
572 share_0 = share;
573
574 quota(res) = yes;
575 tau.lo = 0; tau.l = 0; tau.up = 0.99;
576
577 loop(qsc,
578 *           Assign target shares for renewables in electricity production
579           share = min(1, (share_0 + 20/100* (ord(qsc)-1)/(card(qsc)-1)));
580
581           solve mcp_hybrid using mcp;
582
583           supply(qsc,t)  = ele.l(t)  + epsilon;
584           ev(qsc)        = 100 * (c.l-1) + epsilon;
585           subsidy(qsc)   = 100*tau.l + epsilon;
586 );
587
588 $setglobal labels qsc
589
590 report(qsc,"ev") = ev(qsc);
591 $setglobal gp_opt2 "set title 'Welfare changes'"
592 $setglobal gp_opt3 "set xlabel 'Green quota in % of overall electricity supply'"
593 $setglobal gp_opt4 "set ylabel 'Equivalent variation in income (%)'"
594 $libinclude plot report
595 display report;
596 report(qsc,"ev") = 0;
597
598 $setglobal gp_opt2 "set title 'Electricity supply by technology'"

```



```

599 $setglobal gp_opt3 "set xlabel 'Green quota in % of overall electricity supply'"
600 $setglobal gp_opt4 "set ylabel 'Activity level of technologies'"
601 $libinclude plot supply
602
603 report(qsc,"subsidy") = subsidy(qsc);
604 $setglobal gp_opt2 "set title 'Subsidy on renewables'"
605 $setglobal gp_opt3 "set xlabel 'Green quota in % of overall electricity supply'"
606 $setglobal gp_opt4 "set ylabel 'Subsidy rate (% of electricity price)'"
607 $libinclude plot report
608 display report;
609 report(qsc,"subsidy") = 0;
610
611 *      Re-initialize parameterization for subsequent scenarios
612 share = share_0;
613 quota(res) = no;
614 tau.fx = 0;
615 *=====
616 *      Scenario 3: Carbon taxation (double dividend)
617
618 *      First re-specify base year (benchmark) to public good extension
619 mcp_hybrid.iterlim      = 0;
620
621 dd  = 1;
622 g.lo = 0; g.up = + inf; govt.lo = 0; govt.up = + inf;
623 g0  = 0.2 *(-sam("roi","ra"));
624 tc0 = g0/((-sam("roi","ra")) - g0);
625 display g0, tc0;
626
627 *      Relax fixed variables
628 g.lo = 0; g.up = +inf; pg.lo = 0; pg.up = +inf; govt.lo = 0; govt.up = + inf;
629 pcarb.lo = 0; pcarb.up = + inf;
630
631 *      Initially, we assume that lump-sum transfers are active
632 *      as the equal-yield instrument
633 phi_ls.l  = 0; phi_ls.lo = -inf; phi_ls.up = +inf;
634 phi_tc.fx = 1;
635
636 *      Assign base year carbon emissions (at shadow price of zero)
637 carblim = sum(ff, sam(ff,ff)*carbon(ff));
638 pcarb.l = 0;
639
640 *      Benchmark replication check for the model with public good extension
641 *      Initialize activities and prices

```

```

642 roi.l = 1; ele.l(xt)= xtelec("ele",xt); ele.l(nt) = 0; s.l(ff) = 1; c.l = 1;
643 proi.l = 1; pele.l = 1; pf.l(ff) = 1; pl.l = 1; pk.l = 1; pr.l(ff) = 1; pg.l = 1;
644 pkx.l(t)$((-xtelec("capital",t))$shortrun) = 1; plim.l(t)$limit(t) = 0;
645 pc.l = 1; pn.l(n) = 0; ra.l = c0; govt.l = g0;
646
647 *      Install lower bounds on prices to avoid division by zero in MCP formulation
648 proi.lo = 1e-5; pele.lo = 1e-5; pf.lo(ff) = 1e-5; pl.lo = 1e-5; pk.lo = 1e-5; pr.lo(ff) = 1e-5;
649 pkx.lo(t)$((-xtelec("capital",t))$shortrun) = 1e-5; pc.lo = 1e-5; pg.lo = 1e-5;
650
651 *      Check the re-specified benchmark:
652 *      - marginal of all active activities must be zero
653 *      - marginal of all positive prices must be zero
654 *      - marginal of all positive incomes must be zero
655
656 mcp_hybrid.iterlim = 0;
657
658 solve mcp_hybrid using mcp;
659
660 *      Relax iteration limit
661 mcp_hybrid.iterlim = 4000;
662
663
664 *      Specification of carbon tax scenarios based on exogenous emission reduction targets
665 set      csc  Carbon abatement scenarios scenarios / 0, 5, 10, 15, 20/;
666
667 parameter carbon_0      Benchmark capacity limits;
668 parameter ev_           Report parameter for welfare changes;
669
670 carbon_0 = carblim;
671
672 display carbon_0;
673
674 loop(csc,
675 *      Assign carbon emission limit
676      carblim = (1 - 0.2*(ord(csc)-1)/(card(csc)-1))*carbon_0;
677
678 *      Activate lump-sum transfer as recycling instrument
679 phi_ls.l = 0; phi_ls.lo = -inf; phi_ls.up = +inf;
680 phi_tc.fx = 1;
681
682      solve mcp_hybrid using mcp;
683
684      ev_(csc,"ls")      = 100 * (c.l-1) + epsilon;

```

```

685
686 *      Activate consumption tax as recycling instrument
687 phi_tc.l = 1; phi_tc.lo = -0.99; phi_tc.up = +inf;
688 phi_ls.fx = 0;
689      solve mcp_hybrid using mcp;
690
691      ev_(csc,"tc")          = 100 * (c.l-1) + epsilon;
692 );
693
694 $setglobal labels csc
695 $setglobal gp_opt2 "set title 'Welfare changes'"
696 $setglobal gp_opt3 "set xlabel 'Carbon emission reduction (in % vis--vis base year)'"
697 $setglobal gp_opt4 "set ylabel 'Equivalent variation in income (%)'"
698 $libinclude plot ev_
699 display ev_;
700 ev_(csc,"tc") = 0; ev_(csc,"ls") = 0;
701
702 *      Re-initialize parameterization for subsequent policy scenarios
703 dd = 0; g0 = 0; tc0 = 0;

```

## 5.2 MPSGE Formulation

```
1 $Title  Static maquette of integrated TD/BU hybrid model
2
3 *      Model formulation in meta-language MPSGE
4 *      (see Rutherford 1995 for documentation)
5
6 *=====
7 * Model code for stylzed integrated bottom-up/top-down analysis of energy
8 * policies based on:
9 *
10 *      ZEW Discussion Paper 05-28
11 *      Integrating Bottom-Up into Top-Down:
12 *      A Mixed Complementarity Approach
13 *
14 * Contact the authors at: boehringer@zew.de; rutherford@colorado.edu
15 *=====
16
17 * For plotting the results you must have installed the gnuplot-shareware
18 * (see http://debreu.colorado.edu/gnuplot/gnuplot.htm for downloads)
19
20 *=====
21 *      List of parameters subject to sensitivity analysis
22 *      The user can change the default settings.
23
24 * Choice of key elasticities:
25 *      Elasticity of substitution in final consumption
26 $if not setglobal esub_c $setglobal esub_c 0.5
27
28 *      Elasticity in gas supply
29 $if not setglobal esub_gas $setglobal esub_gas 1.5
30
31 *      Elasticity in coal supply
32 $if not setglobal esub_coal $setglobal esub_coal 3
33
34 *      Elasticity in oil supply
35 $if not setglobal esub_oil $setglobal esub_oil 1.5
36
37
38 * Choice of resource availability for renewables:
39 * (as a fraction of base-year total electricity production)
40 *      Potential wind supply - (%)
41 $if not setglobal p_wind $setglobal p_wind 10
```

```

42
43 *      Potential solar supply - (%)
44 $if not setglobal p_sun $setglobal p_sun 10
45
46 *      Potential biomass supply - (%)
47 $if not setglobal p_trees $setglobal p_trees 10
48
49
50 * Cost disadvantage of initial slack technologies:
51 *      Wind energy premium (%)
52 $if not setglobal c_wind $setglobal c_wind 10
53
54 *      Solar energy premium (%)
55 $if not setglobal c_solar $setglobal c_solar 10
56
57 *      Biomass energy premium (%)
58 $if not setglobal c_biomass $setglobal c_biomass 10
59
60
61 * Other central model assumptions:
62 *      Time horizon (short, long)
63 *      N.B.: For short-run analysis capital is immobile across sectors
64 $if not setglobal horizon $setglobal horizon long
65
66 *=====
67
68
69 *      Assign user-specific changes of default assumptions
70 scalar shortrun      Flag for short-run capital mobility/1/;
71
72 $if "%horizon%"=="long" shortrun=0;
73
74 *      Elasticities of substitution (ESUB)
75 scalar esub_c      Elasticity of substitution in final demand /%esub_c%/
76      esub_ele      ESUB between electricity and oil in final demand /0.5/
77      esub_k_e      ESUB between capital and energy in ROI production /0.5/
78      esub_l_ke      ESUB between labor and other inputs in ROI production /0.8/;
79
80 set      t      Electricity Technologies (current and future)
81      /coal,gas,nuclear,hydro,wind,solar,biomass/;
82
83 set      xt(t)      Existing technologies /coal,gas,nuclear,hydro/;
84

```

```

85 set      nt(t)    New vintage technologies /wind,solar,biomass/;
86
87 set      ff       Fossil fuel inputs /coa, gas, oil/;
88
89 set      n        Natural resources /wind, sun, trees/;
90
91
92 set      res(t)   Renewable energy sources /hydro, wind, solar, biomass/;
93
94 *        The following data table describes an economic equilibrium in
95 *        the base year:
96
97
98 table sam  Base year social accounting matrix
99
100         roi      coa      gas      oil      ele      ra
101 roi      200      -5       -5       -10      -10     -170
102 coa              15              -15
103 gas              15              -15
104 oil              30              -30
105 ele      -10              60      -50
106 capital -80              -20      100
107 labor    -110     -5       -5       -10              130
108 rent              -5       -5       -10              20      ;
109
110 parameter carbon(ff)  Carbon coefficients /oil 1, gas 1, coa 2/;
111
112 scalar  carblim      Carbon target /0/;
113
114 parameter  esub_ff(ff) Elasticity of substitution in fossil fuel production
115           /gas %esub_gas%, coa %esub_coal%, oil %esub_oil%/;
116
117 *        The following data tables describes electricity generation in
118 *        the base year as well as the technology coefficients for technologies
119 *        which are inactive in the base year (wind, solar, biomass). Inactive
120 *        technologies are by defaults %c_****% more costly.
121
122 table xtelec  Electricity technologies - extant (initially active)
123
124         coal      gas      nuclear hydro
125 ele      20       20          12      8
126 roi      -1       -1          -8
127 gas              -15

```

```

128 coa      -15
129 capital  -4      -4      -4      -8;
130
131
132 table ntelec Electricity technologies - new vintage (initially inactive)
133
134          wind      solar      biomass
135 ele      1.0      1.0      1.0
136 roi      -.2      -.3      -.4
137 capital  -.9      -.8      -.7
138 wind     -1.0
139 sun              -1.0
140 trees              -1.0;
141
142
143 *          Adjust the cost coefficients for initially inactive technologies
144 *          according to user assumptions:
145 set xk /roi, capital/;
146
147 ntelec(xk,"wind")    = ntelec(xk,"wind")    * (100+%c_wind%)/110;
148 ntelec(xk,"solar")   = ntelec(xk,"solar")   * (100+%c_solar%)/110;
149 ntelec(xk,"biomass") = ntelec(xk,"biomass") * (100+%c_biomass%)/110;
150
151
152 *          Specify limits (resource or policy constraints) to the availability
153 *          of technologies
154
155 parameter limit      Electricity supply limits on extant technologies /
156      nuclear          12
157      hydro            8 /;
158
159 parameter nrsupply(n) Natural resource supplies (fraction of base output)/
160      wind              %p_wind%
161      sun                %p_sun%
162      trees              %p_trees% /;
163
164 nrsupply(n) = nrsupply(n)/100 * sam("ele","ele");
165
166 parameter c0      Baseyear final consumption;
167 c0 = (-sam("roi","ra")-sam("ele","ra")-sam("oil","ra"));
168
169
170 set      quota(t)  Flag for technologies contributing to green quota;

```

```

171 quota(t) = no;
172
173 scalar   share      Target share for green quota /0/;
174
175 *          By default we might set target share for green quota at base year level
176 share = sum(t$res(t), xtelec("ele",t))/sum(t, xtelec("ele",t));
177 display share;
178
179 scalar
180         dd      Flag for double dividend policy analysis /0/,
181         ls      Flag for lump-sum revenue-recycling      /0/,
182         vat      Flag for VAT revenue recycling           /0/,
183         g0       Base year public consumption             /0/,
184         tc0      Base year consumption tax                /0/;
185
186 *          MPSGE formulation of the hybrid model
187 $ontext
188
189 $model:mps_hybrid
190
191 $sectors:
192         roi      ! Aggregate output
193         ele(t)   ! Production levels for electricity by technology
194         s(ff)    ! Fossil fuel supplies
195         c        ! Aggregate consumption (utility) formation
196         g$dd     ! Public good provision
197
198 $commodities:
199         proi     ! Price of aggregate output
200         pele     ! Price of electricity
201         pf(ff)   ! Price of oil and gas
202         pl       ! Wage rate
203         pk       ! Price of malleable capital for X (and NT elec)
204         pr(ff)   ! Rent on fossil fuel resources
205         pn(n)    ! Rent on natural resources
206         pc       ! Consumption (utility) price index
207         pg$dd    ! Price of public consumption
208         plim(t)$limit(t)                                ! Shadow price on electricity expansion
209         pkx(t)$((-xtelec("capital",t))$shortrun) ! Price of capital to extant technologies
210         pcarb$carblim                                    ! Carbon tax rate
211
212 $consumers:
213         ra       ! Representative household

```



```

214         govt$dd ! Government
215
216 $auxiliary:
217         tau$card(quota) ! Uniform subsidy rate on renewable energy
218         phi_ls$dd       ! Lump-sum recycling
219         phi_tc$dd       ! Consumption tax recycling
220
221
222 *      Aggregate output:
223
224 $prod:roi s:esub_l_ke ke:esub_k_e
225         o:proi  q:sam("roi","roi")
226         i:pl    q:(-sam("labor","roi"))
227         i:pk    q:(-sam("capital","roi")) ke:
228         i:pele  q:(-sam("ele","roi"))    ke:
229
230 *      Extant electricity:
231
232 $prod:ele(xt)
233         o:pele          q:1   raa:ra   n:tau$quota(xt)   m:(-1)$quota(xt)
234         i:proi          q:(-xtelec("roi",xt)/xtelec("ele",xt))
235         i:pf(ff)        q:(-xtelec(ff,xt)/xtelec("ele",xt))
236         i:pkx(xt)$shortrun q:(-xtelec("capital",xt)/xtelec("ele",xt))
237         i:pk$(not shortrun) q:(-xtelec("capital",xt)/xtelec("ele",xt))
238         i:plim(xt)$limit(xt) q:1
239
240 *      New vintage electricity:
241
242 $prod:ele(nt)
243         o:pele  q:1   a:ra   n:tau$quota(nt) m:(-1)$quota(nt)
244         i:proi  q:(-ntelec("roi",nt))
245         i:pk    q:(-ntelec("capital",nt))
246         i:pn(n) q:(-ntelec(n,nt))
247
248 $prod:s(ff) s:0  r:esub_ff(ff)  xl(r):0
249         o:pf(ff)          q:sam(ff,ff)
250         i:pcarb$carbblim q:(carbon(ff)*sam(ff,ff))
251         i:proi            q:(-sam("roi",ff))    xl:
252         i:pl              q:(-sam("labor",ff))  xl:
253         i:pr(ff)          q:(-sam("rent",ff))   r:
254
255 $prod:c s:esub_c e:esub_ele
256         o:pc              q:c0

```

```

257          i:proi          q:(-sam("roi","ra"))/(1+tc0$dd) p:(1+tc0$dd)
258 + a:govt$dd n:phi_tc$dd m:tc0$dd
259          i:pele          q:(-sam("ele","ra")) e:
260          i:pf("oil")      q:(-sam("oil","ra")) e:
261
262 $demand:ra
263          d:pc              q:c0
264          e:pk      q:(-sam("capital","roi")+sum(xt,(-xtelec("capital",xt)))$(not shortrun))
265          e:pkx(xt)$shortrun      q:(-xtelec("capital",xt))
266          e:pl              q:(sam("labor","ra"))
267          e:pr(ff)          q:(-sam("rent",ff))
268          e:pn(n)           q:nrsupply(n)
269          e:pcarb$carblim$(not dd) q:carblim
270          e:plim(xt)$limit(xt)      q:limit(xt)
271          e:pc$dd           q:(-1)      r:phi_ls$dd
272
273
274 $demand:govt$dd
275          d:pg      q:g0
276          e:pc      q:1      r:phi_ls
277          e:pcarb$carblim      q:carblim
278
279 $prod:g$dd
280          0:pg      q:g0
281          i:proi      q:g0
282
283
284 $constraint:tau$card(quota)
285          sum(t$res(t), ele(t)) =e= share*sum(t, ele(t));
286
287
288 $constraint:phi_ls$dd
289          g =e= 1;
290
291 $constraint:phi_tc$dd
292          g=e= 1;
293
294 $offtext
295 $sysinclude mpsgeset mps_hybrid
296
297 *      In the base year new-vintage technologies are inactive
298 *      and the prices of backstop natural resources are zero
299 *      Extant technologies with capacity limits are assumed to

```

```

300 *      operate at the upper bound with a zero shadow value in the
301 *      base year
302
303 ele.l(nt) = 0;
304 pn.l(n)   = 0;
305 plim.l(xt) = 0;
306
307 ele.l(xt) = xtelec("ele",xt);
308
309 *      Benchmark replication check
310 mps_hybrid.iterlim = 0;
311 $include mps_hybrid.gen
312 solve mps_hybrid using mcp;
313
314 display "The precision of the benchmark dataset is:", mps_hybrid.objval;
315 abort$(ABS(mps_hybrid.objval) gt 1e-4)"MPSGE model does not calibrate";
316
317
318 *      Relax iteration limit for counterfactual policy analysis
319 mps_hybrid.iterlim      = 4000;
320
321
322 *=====
323 *      Analysis of policy scenarios (as laid out in the paper)
324 *
325 *      (i)   gradual nuclear phase-out
326 *      (ii)  target quota for renewables (green quota)
327 *      (iii) carbon taxation (environmental tax reform)
328
329
330 *      Define report parameters
331 parameter
332     ev(*)           Equivalent variation in income
333     supply(*,*)     Electricity supply by technology
334     carbtax(*)       Carbon permit price
335     subsidy          Subsidy rate on electricity from renewables
336     report           Report default parameter;
337
338 scalar epsilon /1.e-5/;
339
340
341 *=====
342 *      Scenario 1: Gradual nuclear phase-out

```

```

343
344 set      nsc  Nuclear phase scenarios / 0, 25, 50, 75, 100/;
345
346 parameter limit_0      Base year capacity limits;
347 limit_0("nuclear") = limit("nuclear");
348
349 loop(nsc,
350
351 *      Assign available capacity for nuclear power
352      limit("nuclear") = (1 - (ord(nsc)-1)/(card(nsc)-1))*limit_0("nuclear");
353 *      If nuclear capacity is set to zero, assure complete nuclear phase out
354      if ((not limit("nuclear")),
355          ele.fx("nuclear") = 0;
356      );
357 $include mps_hybrid.gen
358      solve mps_hybrid using mcp;
359      supply(nsc,t)      = ele.l(t)  + epsilon;
360      ev(nsc)            = 100 * (c.l-1) + epsilon ;
361
362 );
363
364
365 $setglobal labels nsc
366 $setglobal gp_opt0 "set data style linespoints"
367
368 $setglobal gp_opt1 "set key below"
369 report(nsc,"ev") = ev(nsc);
370 $setglobal gp_opt2 "set title 'Welfare changes'"
371 $setglobal gp_opt3 "set xlabel 'Nuclear capacity reduction (% vis--vis BaU)'"
372 $setglobal gp_opt4 "set ylabel 'Equivalent variation in income (%)'"
373 $libinclude plot report
374 display report;
375 report(nsc,"ev") = 0;
376
377
378 $setglobal gp_opt2 "set title 'Electricity supply by technology'"
379 $setglobal gp_opt3 "set xlabel 'Nuclear capacity reduction (% vis--vis BaU)'"
380 $setglobal gp_opt4 "set ylabel 'Activity level of technologies'"
381 $libinclude plot supply
382
383 *      Re-initialize parameterization for subsequent scenarios
384 limit("nuclear") = limit_0("nuclear");
385 ele.lo("nuclear") = 0; ele.up("nuclear") = +inf;

```

```

386 ele.l("nuclear")=xtelec("ele","nuclear");
387
388
389 *=====
390 *      Scenario 2: Green quotas
391
392 set      qsc  Green quota scenarios / 0 13, 5 18, 10 23, 15 28, 20 33/;
393 *      Note:   We start from the base year situation without binding target
394 *              share and then increase the share iteratively by 5%.
395 *              The descriptive text for scenario set elements captures
396 *              the actual target level of green electricity as percent
397 *              in overall electricity production (base year quota is 13%).
398 *              The plot-command picks up the descriptive text as
399 *              scenario labels when produce a graphical exposition of results.
400
401
402 parameter share_0      Base year renewable share;
403 share_0 = share;
404
405 quota(res) = yes;
406
407
408 loop(qsc,
409 *      Assign target shares for renewables in electricity production
410      share = min(1, (share_0 + 20/100* (ord(qsc)-1)/(card(qsc)-1)));
411
412 $include mps_hybrid.gen
413      solve mps_hybrid using mcp;
414
415      supply(qsc,t)   = ele.l(t) + epsilon;
416      ev(qsc)         = 100 * (c.l-1) + epsilon;
417      subsidy(qsc)    = 100*tau.l + epsilon;
418 );
419
420 $setglobal labels qsc
421
422 report(qsc,"ev") = ev(qsc);
423 $setglobal gp_opt2 "set title 'Welfare changes'"
424 $setglobal gp_opt3 "set xlabel 'Green quota in % of overall electricity supply'"
425 $setglobal gp_opt4 "set ylabel 'Equivalent variation in income (%)'"
426 $libinclude plot report
427 display report;
428 report(qsc,"ev") = 0;

```

```

429
430 $setglobal gp_opt2 "set title 'Electricity supply by technology'"
431 $setglobal gp_opt3 "set xlabel 'Green quota in % of overall electricity supply'"
432 $setglobal gp_opt4 "set ylabel 'Activity level of technologies'"
433 $libinclude plot supply
434
435 report(qsc,"subsidy") = subsidy(qsc);
436 $setglobal gp_opt2 "set title 'Subsidy on renewables'"
437 $setglobal gp_opt3 "set xlabel 'Green quota in % of overall electricity supply'"
438 $setglobal gp_opt4 "set ylabel 'Subsidy rate (% of electricity price)'"
439 $libinclude plot report
440 display report;
441 report(qsc,"subsidy") = 0;
442
443 *      Re-initialize parameterization for subsequent scenarios
444 share = share_0;
445 quota(res) = no;
446 $exit
447 *=====
448 *      Scenario 3: Carbon taxation (double dividend)
449
450 *      First re-calibrate base year (benchmark) to public good extension
451 mps_hybrid.iterlim      = 0;
452
453 dd = 1;
454 g0 = 0.2 *(-sam("roi","ra"));
455 tc0 = g0/((-sam("roi","ra")) - g0);
456 display g0, tc0;
457
458 *      Initially, we assume that lump-sum transfers are active
459 *      as the equal-yield instrument
460 phi_ls.l = 0; phi_ls.lo = -inf; phi_ls.up = +inf;
461 phi_tc.fx = 1;
462
463 *      Assign base year carbon emissions (at shadow price of zero)
464 carblim = sum(ff, sam(ff,ff)*carbon(ff));
465 pcarb.l = 0;
466
467 *      Benchmark replication check for the model with public good extension
468 *      Initialize activities and prices
469 roi.l = 1; ele.l(xt)= xtelec("ele",xt); ele.l(nt) = 0; s.l(ff) = 1; c.l = 1;
470 proi.l = 1; pele.l = 1; pf.l(ff) = 1; pl.l = 1; pk.l = 1; pr.l(ff) = 1;
471 pkx.l(t)$((-xtelec("capital",t))$shortrun) = 1; plim.l(t)$limit(t) = 0;

```

```

472 pc.l = 1; pn.l(n) = 0; ra.l = c0; govt.l = g0;
473
474 mps_hybrid.iterlim = 0;
475 $include mps_hybrid.gen
476 solve mps_hybrid using mcp;
477
478 display "The precision of the re-specified benchmark dataset is:", mps_hybrid.objval;
479 abort$(ABS(mps_hybrid.objval) gt 1e-4)"MPSGE model does not calibrate";
480
481 *          Relax iteration limit
482 mps_hybrid.iterlim = 4000;
483
484
485 *          Specification of carbon tax scenarios based on exogenous emission reduction targets
486 set      csc  Carbon abatement scenarios scenarios / 0, 5, 10, 15, 20/;
487
488 parameter carbon_0      Benchmark capacity limits;
489 parameter ev_           Report parameter for welfare changes;
490
491 carbon_0 = carblim;
492
493 display carbon_0;
494
495 loop(csc,
496 *          Assign carbon emission limit
497      carblim = (1 - 0.2*(ord(csc)-1)/(card(csc)-1))*carbon_0;
498
499 *          Activate lump-sum transfer as recycling instrument
500 phi_ls.l = 0; phi_ls.lo = -inf; phi_ls.up = +inf;
501 phi_tc.fx = 1;
502 $include mps_hybrid.gen
503      solve mps_hybrid using mcp;
504      ev_(csc,"ls")          = 100 * (c.l-1) + epsilon;
505
506 *          Activate consumption tax as recycling instrument
507 phi_tc.l = 1; phi_tc.lo = -0.99; phi_tc.up = +inf;
508 phi_ls.fx = 0;
509 $include mps_hybrid.gen
510      solve mps_hybrid using mcp;
511      ev_(csc,"tc")          = 100 * (c.l-1) + epsilon;
512 );
513
514 $setglobal labels csc

```

```

515 $setglobal gp_opt2 "set title 'Welfare changes'"
516 $setglobal gp_opt3 "set xlabel 'Carbon emission reduction (in % vis--vis base year)'"
517 $setglobal gp_opt4 "set ylabel 'Equivalent variation in income (%)'"
518 $libinclude plot ev_
519 display ev_;
520 ev_(csc,"tc") = 0; ev_(csc,"ls") = 0;
521
522 *      Re-initialize parameterization for subsequent policy scenarios
523 dd = 0; g0 = 0; tc0 = 0;

```