View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Research Papers in Economics

ECONSTOR
WWW.ECONSTOR.EU

Der Open-Access-Publikationsserver der ZBW – Leibniz-Informationszentrum Wirtschaft
The Open Access Publication Server of the ZBW – Leibniz Information Centre for Economics

Böhringer, Christoph; Rutherford, Thomas F.

Working Paper

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

ZEW Discussion Papers, No. 05-28

Provided in cooperation with:
Zentrum für Europäische Wirtschaftsforschung (ZEW)

Suggested citation: Böhringer, Christoph; Rutherford, Thomas F. (2005) : Integrating Bottom-Up into Top-Down: A Mixed Complementarity Approach, ZEW Discussion Papers, No. 05-28, http://hdl.handle.net/10419/24137

Nutzungsbedingungen:
Die ZBW räumt Ihnen als Nutzerin/Nutzer das unentgeltliche, räumlich unbeschränkte und zeitlich auf die Dauer des Schutzrechts beschränkte einfache Recht ein, das ausgewählte Werk im Rahmen der unter
→ http://www.econstor.eu/dspace/Nutzungsbedingungen
nachzulesenden vollständigen Nutzungsbedingungen zu vervielfältigen, mit denen die Nutzerin/der Nutzer sich durch die erste Nutzung einverstanden erklärt.

Terms of use:
The ZBW grants you, the user, the non-exclusive right to use the selected work free of charge, territorially unrestricted and within the time limit of the term of the property rights according to the terms specified at
→ http://www.econstor.eu/dspace/Nutzungsbedingungen
By the first use of the selected work the user agrees and declares to comply with these terms of use.

ZBW
Leibniz-Informationszentrum Wirtschaft
Leibniz Information Centre for Economics

Mitglied der
Leibniz-Gemeinschaft

Discussion Paper No. 05-28

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

Christoph Böhringer and Thomas F. Rutherford

ZEW
Zentrum für Europäische
Wirtschaftsforschung GmbH

Centre for European
Economic Research

Discussion Paper No. 05-28

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

Christoph Böhringer and Thomas F. Rutherford

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

Christoph Böhringer
Centre for European Economic Research (ZEW), Mannheim, Germany
Department of Economics, University of Heidelberg, Germany
boehringer@zew.de

Thomas F. Rutherford
Department of Economics, University of Colorado, Boulder, U.S.A.
tom@mpsge.org

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.[1]

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.[2] The third approach provides

---

[1] In addition, top-down models may not assure fundamental physical restrictions such as the conservation of matter and energy.

[2] 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 *c*omputable *g*eneral *e*quilibrium (CGE) models for energy policy analysis.[3] 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.[4]

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.

---

[3] 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]).

[4] "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.:

$$-\Pi_j(p) = -a_j^T(p)p \geq 0 \tag{1}$$

  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 $\nabla\Pi_j(p)$.[5]

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

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

  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.:

$$M_h = p^T w_h \tag{3}$$

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

$$y_i \Pi_j(p) = 0 \tag{4}$$

---

[5] Input coefficients have a negative sign; output coefficients are positive.

$$p_i[\sum_j (y_i \nabla \Pi_j(p) + \sum_h w_h) - \sum_h d_h(p, M_h)] = 0 \tag{5}$$

$$M_h(M_h - p^T w_h) = 0 \tag{6}$$

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]):[6]

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

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

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 (sevice) j:

$$\min \sum_i \sum_t p_i a_{ijt} y_{jt} \tag{7}$$

subject to

$$\sum_t y_{jt} + \sum_{i \neq j} a_{ji} \bar{y}_i + \sum_h w_{jh} \geq \sum_h \bar{d}_{jh}$$

$$y_{jt} \leq \sum_h w_{hjt}$$

where:

---

[6] 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:

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

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

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

where:

π_j is the shadow price on the supply-demand balance for energy good j, and

λ_{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:

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

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,

σ 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.[7] The unit-profit function for fossil fuel production ($i \in FF$) is:

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

where:

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

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

---

[7] The latter can then be calibrated in consistency with empirical estimates for price elasticities of fossil fuel supply.

θ_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

σ_i is the elasticity of substitution between the fossil fuel ressource 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 electricty sector. Rather than describing electricity generation by means of a single continuous smooth CES production function we capture production possibilities by discrete (Leontief-fix) 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:

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

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:

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

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,

σ_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:

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

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 ressource 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 [8] 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:

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

  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.

---

[8] 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:

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

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

$$\bar{Q}_i \geq \frac{\partial \Pi^Y}{\partial p_{Q,i}} Y_i \tag{18}$$

- Market clearence for capacity bounds:

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

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

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

- Market clearance for electricity:

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

- Market clearance for the final consumption composite:

$$C \geq \frac{M}{p_C} \tag{22}$$

Figure 1 provides a diagrammatic structure of our stylized economy using the notations of our algebraic exposition (for the sake of transparency, we do no 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

	ROI	*COA*	*GAS*	*OIL*	*ELE*	*RA*
ROI	200	-5	-5	-10	-180	
COA		15			-15	
GAS			15		-15	
OIL				30		-30
ELE	-10				60	-50
Capital	-80				-20	100
Labor	-110	-5	-5	-10		130
Rent		-5	-5	-10		20

Key	
ROI:	rest of industry
COA:	coal
GAS:	gas
OIL:	oil
ELE:	electricity
RA:	household

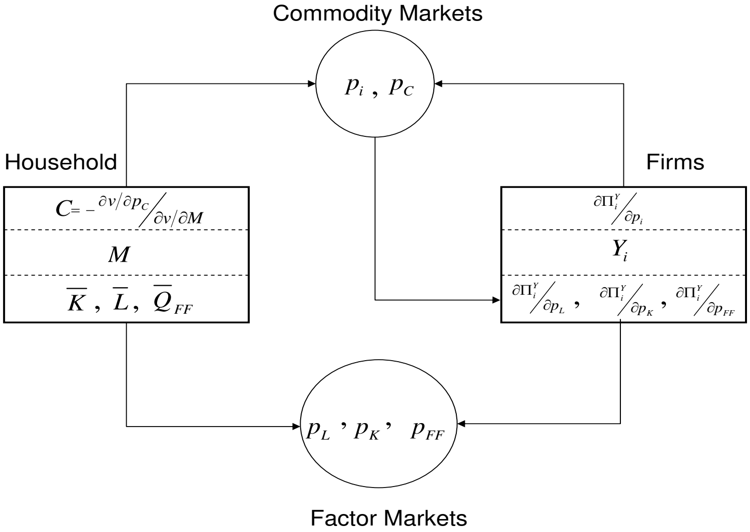

Figure 1: *Diagrammatic Structure of Stylized Economy*

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.[9] 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.[10]

---

[9] 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.

[10] 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
ELE	20	20	12	8
ROI	-1	-1	-8	
GAS		-15		
COA	-15			
Capital	-4	-4	-4	-8

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

	wind	solar	biomass
ELE	1	1	1
ROI	-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.[11] Our results section below is restrained to the central case parameterization

---

[11] 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 accomodated 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").

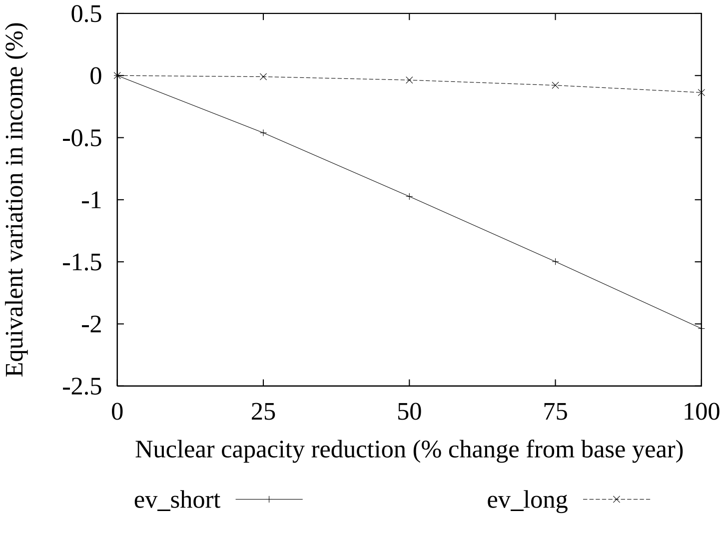

Figure 2: *Welfare Changes for Nuclear Phase-Out*

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 acitivites (apart from hydro which is already operated at the upper bound in the reference situation).

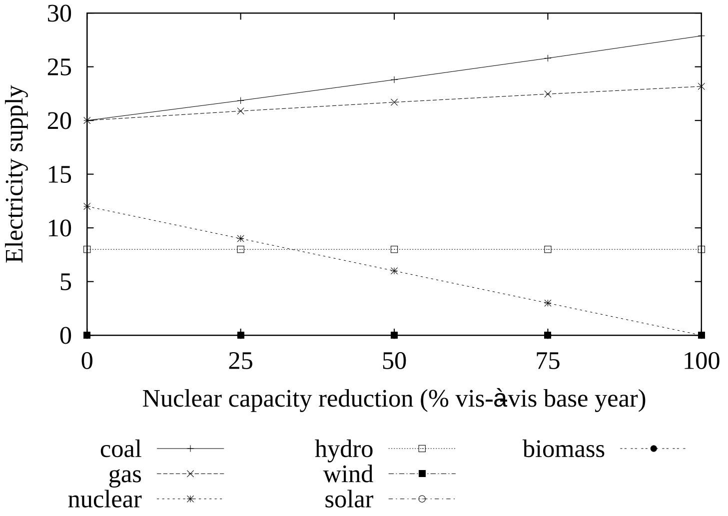

Figure 3: *Technology Shifts in Power Production for Nuclear Phase-Out*

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.

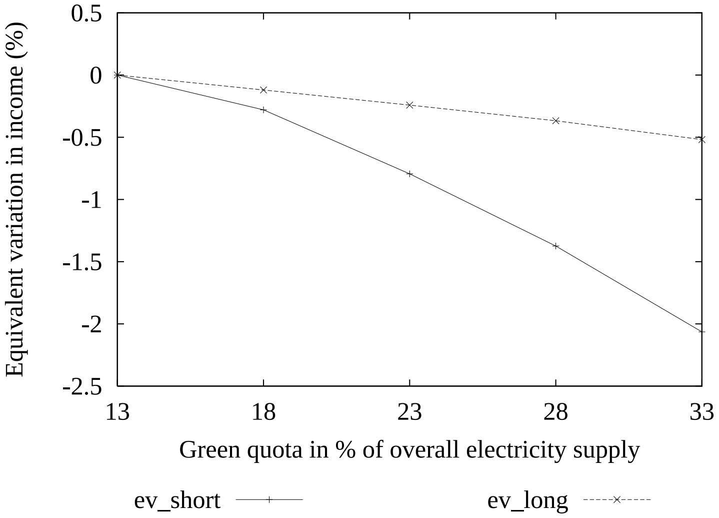

Figure 4: *Welfare Changes under Green Quotas*

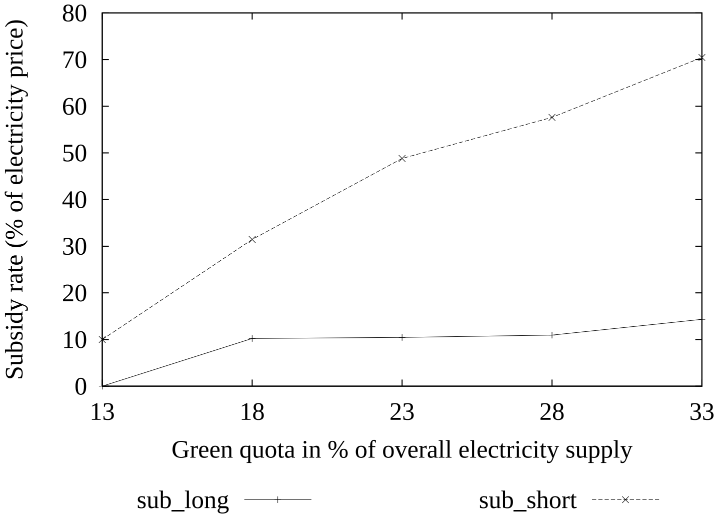

Figure 5: *Subsidy Rate for Green Quotas*

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[12] 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 from emission taxation (Goulder [1995]): Apart form 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).[13]

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.

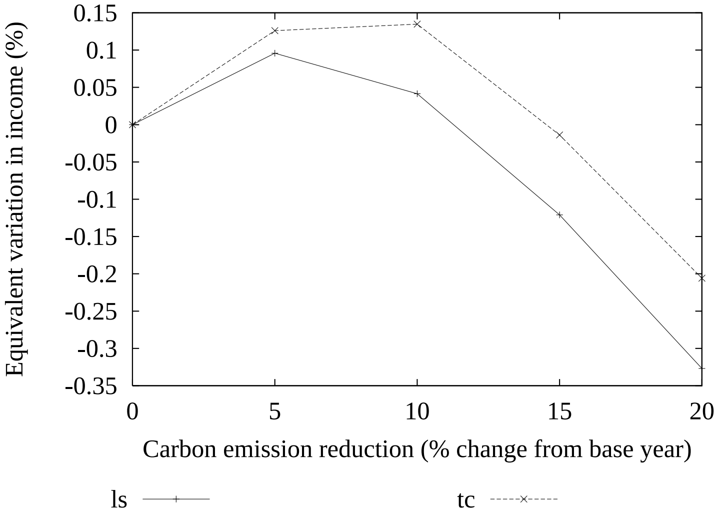

Figure 6: *Welfare Changes for Alternative Environmental Tax Reforms*

---

[12] That is the costs disregarding environmental benefits.

[13] 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 distortonary 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.

References

Bahn, O., S. Kypreos, B. Büeler, and H. J. Luethi, "Modelling an international market of CO_2 emission permits," *International Journal of Global Energy Issues*, 1999, *12*, 283–291.

Böhringer, C., "The Synthesis of Bottom-Up and Top-Down in Energy Policy Modeling," *Energy Economics*, 1998, *20* (3), 233–248.

Brooke, A., D. Kendrick, and A. Meeraus, *GAMS: A Users Guide*, GAMS Development Corp., 1996.

Chipman, J., "Homothetic preferences and aggregation," *Journal of Economic Theory*, 1974, *8*, 26–38.

Dirkse, S. and M. Ferris, "The PATH Solver: A Non-monotone Stabilization Scheme for Mixed Complementarity Problems," *Optimization Methods & Software*, 1995, *5*, 123–156.

European Commission (EC), *Directive 2001/77/EC on the Promotion of Electricity produced from Renewable Energy Sources (RES-E) in the internal electricity market* 2001.

Goulder, L. H., "Environmental taxation and the double dividend: A readers guide," *International Tax and Public Finance*, 1995, *2*, 157–183.

Hofman, K. and D. Jorgenson, "Economic and technological models for evaluation of energy policy," *The Bell Journal of Economics*, 1976, pp. 444–446.

Hogan, W. W. and J. P. Weyant, "Combined Energy Models," in J. R. Moroney, ed., *Advances in the Economics of Energy and Ressources*, 1982, pp. 117–150.

King, B., "What is a SAM?," in "Social Accounting Matrices: A Basis for Planning," Washington D. C.: The World Bank, 1985.

Manne, A. S., "ETA-MACRO: A Model of Energy Economy Interactions," Technical Report, Electric Power Research Institute, Palo Alto, California 1977.

Mathiesen, L., "Computation of Economic Equilibrium by a Sequence of Linear Complementarity Problems," in A. Manne, ed., *Economic Equilibrium - Model Formulation and Solution*, Vol. 23 1985, pp. 144–162.

Messner, S. and L. Schrattenholzer, "MESSAGE-MACRO: Linking an Energy Supply Model with a Macroeconomic Module and Solving Iteratively," *Energy – The International Journal*, 2000, *25* (3), 267–282.

—— **and M. Strubegger**, "Ein Modellsystem zur Analyse der Wechselwirkungen zwischen Energiesektor und Gesamtwirtschaft," *Öffentlicher Sektor – Forschungsmemoranden*, 1987, *13*, 1–24.

OECD, *Database on environmentally related taxes in OECD countries* 2001. Available at: http://www.oecd.org/env/policies/taxes/index.htm.

OECD/IEA, *Nuclear Power in the OECD* 2001. Available at: http://www.iea.org/textbase/nppdf/free/2000/nuclear2001.pdf.

Pressman, I., "A Mathematical Formulation of the Peak-Load Problem," *The Bell Journal of Economics and Management Science*, 1970, *1*, 304–326.

Rutherford, T. F., "Extensions of GAMS for Complementarity Problems Arising in Applied Economics," *Journal of Economic Dynamics and Control*, 1995, *19*, 1299–1324.

____, "Applied General Equilibrium Modelling with MPSGE as a GAMS Subsystem: An Overview of the Modelling Framework and Syntax," *Computational Economics*, 1999, *14*, 1–46.

____, "Sequential Joint Maximization," in J.Weyant, ed., *Energy and Environmental Policy Modeling*, Vol. 18, Kluwer, 1999, chapter 9.

Takayma, T. and G. G. Judge, "Spatial and Temporal Price and Allocation Models," 1971.

Weyant, J. and T. Olavson, "Issues in Modeling Induced Technological Change in Energy, Environment, and Climate Policy," *Journal of Environmental Management and Assessment*, 1999, *1*, 67–85.

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.[14]

Table A1: Equilibrium Conditions

Zero profit conditions

- Macro Production ($i \in ROI$):

$$\begin{aligned} \Pi_i^Y = \quad & p_i - \{(\theta_{L,i} p_L)^{1-\sigma} + (1-\theta_{L,i})[\theta_{ELE,i} p_{ELE}^{1-\sigma_{ELE,i}} \\ & + (1-\theta_{ELE,i}) p_K^{1-\sigma_{ELE,i}}]^{\frac{1-\sigma}{1-\sigma ELE,i}}\}^{\frac{1}{1-\sigma}} \end{aligned} \qquad \perp Y_i$$

- Fossil Fuel Production ($i \in FF$):

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

- Final Consumption:

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

- Electricity production by technology (t):

$$\Pi_t^{ELE} = p_{ELE} - \theta_{ROI,t} p_{ROI} - \theta_{K,t} p_K - \sum_{(i \in FF)} \theta_{FF,t} p_{FF} - p_{U,t} \qquad \perp X_t$$

Market clearence conditions

- Labor:

$$\bar{L} \geq \sum_i \frac{\partial \Pi_i^Y}{\partial p_L} Y_i + \sum_t \frac{\partial \Pi_t^{ELE}}{\partial p_L} X_t \qquad \perp p_L$$

- Capital:

$$\bar{K} \geq \sum_i \frac{\partial \Pi_i^Y}{\partial p_K} Y_i + \sum_t \frac{\partial \Pi_t^{ELE}}{\partial p_K} X_t \qquad \perp p_K$$

- Fossil fuel ressources ($i \in FF$):

$$\bar{Q}_i \geq \frac{\partial \Pi^Y}{\partial p_{Q,i}} Y_i \qquad \perp P_{Q,i}$$

- Capacity constraints ($i \in FF$):

$$\bar{U}_t \geq \frac{\partial \Pi_t^{ELE}}{\partial p_{U,t}} X_t \qquad \perp p_{U,t}$$

- Production goods except for electricity:

---

[14] We use the "$\perp$" operator to indicate complementarity between equilibrium conditions and the respective decision variables.

$$Y_i \geq \sum_j \frac{\partial \Pi_j^Y}{\partial p_i} Y_j + \sum_t \frac{\partial \Pi_t^{ELE}}{\partial p_i} X_t + \frac{\partial \Pi^C}{\partial p_i} C \qquad \perp p_i$$

- Electricity:

$$\sum_t X_t \geq \sum_i \frac{\partial \Pi_i^Y}{\partial p_{ELE}} Y_i + \frac{\partial \Pi^C}{\partial p_{ELE}} C \qquad \perp p_{ELE}$$

- Final consumption composite:

$$C \geq \frac{M}{p_C} \qquad \perp p_C$$

Income balance

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

Table A2: Variables

	Activity variables
Y_i	Production of good i (except for electricity)
C	Aggregate final consumption
X_t	Production of electricity by technology t
	Price variables
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 ressources ($i \in FF$)
p_C	Price of the final consumption composite
	Income variables
M	Income of representative household

Table A3: Cost Shares, Elasticities, and Endowments

Cost shares	
$\theta_{L,i}$	Cost share of labor in production of good i (except for electricitiy)
$\theta_{ELE,i}$	Cost share of electricity in sector-specific capital-electricity composite ($i \in ROI$)
θ_i	Cost share of fossil fuel ressource 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
Elasticities of substitution	
σ	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 ($i \in ROI$)
σ_i	Elasticity of substitution between ressource input and non-ressource inputs in production of fossil fuels ($i \in FF$)
σ_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
Endowments	
$\bar{L}$	Aggregate labor endowment
$\bar{K}$	Aggregate capital endowment
$\bar{Q}_{FF}$	Ressource endowment with fossil fuel FF
$\bar{U}_t$	Capacity of technology t

Appendix B: GAMS Programs

5.1 MCP Formulation

```
$Title  Static maquette of integrated TD/BU hybrid model

*       Model formulation in MCP

*==========================================================================
* Model code for stylzed integrated bottom-up/top-down analysis of energy
* policies based on:
*
*               ZEW Discussion Paper 05-28
*          Integrating Bottom-Up into Top-Down:
*            A Mixed Complementarity Approach
*
* Contact the authors at: boehringer@zew.de; rutherford@colorado.edu
*===========================================================================

* For plotting the results you must have installed the gnuplot-shareware
* (see http://debreu.colorado.edu/gnuplot/gnuplot.htm for downloads)

*===========================================================================
*       List of parameters subject to sensitivity analysis
*       The user can change the default settings.

* Choice of key elasticities:
*       Elasticity of substitution in final consumption
$if not setglobal esub_c $setglobal esub_c 0.5

*       Elasticity in gas supply
$if not setglobal esub_gas  $setglobal esub_gas  1.5

*       Elasticity in coal supply
$if not setglobal esub_coal  $setglobal esub_coal 3

*       Elasticity in oil supply
$if not setglobal esub_oil  $setglobal esub_oil 1.5


* Choice of resource availability for renewables:
* (as a fraction of base-year total electricity production)
*       Potential wind supply - (%)
```

```
$if not setglobal p_wind  $setglobal p_wind  10

*       Potential solar supply - (%)
$if not setglobal p_sun  $setglobal p_sun   10

*       Potential biomass supply - (%)
$if not setglobal p_trees  $setglobal p_trees 10


* Cost disadvantage of inital slack technologies:
*       Wind energy premium (%)
$if not setglobal c_wind  $setglobal c_wind 10

*       Solar energy premium (%)
$if not setglobal c_solar  $setglobal c_solar   10

*       Biomass energy premium (%)
$if not setglobal c_biomass  $setglobal c_biomass 10


* Other central model assumptions:
*       Time horizon (short, long)
*       N.B.: For short-run analysis capital is immobile across sectors
$if not setglobal horizon  $setglobal horizon long

*============================================================================


*       Assign user-specific changes of default assumptions
scalar  shortrun        Flag for short-run capital mobility/1/;

$if "%horizon%"=="long" shortrun=0;

*       Elasticitities of substitution (ESUB)
scalar  esub_c     Elasticity of substituion in final demand /%esub_c%/
        esub_ele   ESUB between electricity and oil in final demand /0.5/
        esub_k_e   ESUB between capital and energy in ROI production /0.5/
        esub_l_ke  ESUB between labor and other inputs in ROI production /0.8/;

set     t       Electricity Technologies (current and future)
                /coal,gas,nuclear,hydro,wind,solar,biomass/;

set     xt(t)   Existing technologies /coal,gas,nuclear,hydro/;
```

```

set     nt(t)   New vintage technologies /wind,solar,biomass/;

set     ff      Fossil fuel inputs /coa, gas, oil/;

set     n       Natural resources /wind, sun, trees/;


set     res(t)  Renewable energy sources /hydro, wind, solar, biomass/;

*       The following data table describes an economic equilibrium in
*       the base year:


table sam    Base year social accounting matrix

        roi     coa     gas     oil     ele     ra
roi     200     -5      -5      -10     -10    -170
coa             15                      -15
gas                     15              -15
oil                             30              -30
ele     -10                              60     -50
capital -80                             -20     100
labor   -110    -5      -5      -10             130
rent            -5      -5      -10              20             ;

parameter carbon(ff)    Carbon coefficients /oil 1, gas 1, coa 2/;

scalar  carblim         Carbon target /0/;

parameter  esub_ff(ff)  Elastictity of substitution in fossil fuel production
        /gas %esub_gas%, coa %esub_coal%, oil %esub_oil%/;

*       The following data tables describes electricy generation in
*       the base year as well as the technology coefficients for technologies
*       which are inactive in the base year (wind, solar, biomass). Inactive
*       technologies are by defaults %c_****% more costly.

table xtelec  Electricty technologies - extant (initially active)

        coal    gas     nuclear hydro
ele       20      20          12     8
roi       -1      -1          -8
```

```
gas             -15
coa      -15
capital   -4     -4          -4    -8;


table ntelec  Electricty technologies - new vintage (initially inactive)

         wind    solar   biomass
ele       1.0      1.0      1.0
roi       -.2      -.3      -.4
capital   -.9      -.8      -.7
wind     -1.0
sun               -1.0
trees                      -1.0;


*       Adjust the cost coefficients for initially inactive technologies
*       according to user assumptions:
set xk /roi, capital/;

ntelec(xk,"wind")    = ntelec(xk,"wind")    * (100+%c_wind%)/110;
ntelec(xk,"solar")   = ntelec(xk,"solar")   * (100+%c_solar%)/110;
ntelec(xk,"biomass") = ntelec(xk,"biomass") * (100+%c_biomass%)/110;


*       Specify limits (resource or policy constraints) to the availability
*       of technologies

parameter limit    Electricty supply limits on extant technologies /
        nuclear         12
        hydro            8 /;

parameter  nrsupply(n)  Natural resource supplies (fraction of base output)/
        wind            %p_wind%
        sun             %p_sun%
        trees           %p_trees% /;

nrsupply(n) = nrsupply(n)/100 * sam("ele","ele");

parameter c0    Baseyear final consumption;
c0 = (-sam("roi","ra")-sam("ele","ra")-sam("oil","ra"));


```

```
set     quota(t)  Flag for technologies contributing to green quota;
quota(t) = no;

scalar  share   Target share for green quota /0/;

*       By default we might set target share for green quota at base year level
share = sum(t$res(t), xtelec("ele",t))/sum(t, xtelec("ele",t));
display share;

scalar
        dd      Flag for double dividend policy analysis /0/,
        ls      Flag for lump-sum revenue-recyling       /0/,
        vat     Flag for VAT revenue recycling           /0/,
        g0      Base year public consumption             /0/,
        tc0     Base year consumption tax                /0/;


positive variables
*       Activitiy levels
roi     Aggregate output
ele(t)  Production levels for electricity by technology
s(ff)   Fossil fuel supplies
c       Aggregate consumption (utility) formation
g       Public good provision

*       Price levels
proi    Price of aggregate output
pele    Price of electricty
pf(ff)  Price of oil and gas
pl      Wage rate
pk      Price of malleable capital for X (and NT elec)
pr(ff)  Rent on fossil fuel resources
pn(n)   Rent on natural resources
pc      Consumption (utility) price index
pg      Price of public consumption
plim(t) Shadow price on electricity expansion
pkx(t)  Price of capital to extant technologies
pcarb   Carbon tax rate

*       Income variables
ra      Representative household
govt    Government

```

```
*       Endogenous taxes or subsidies
tau     Uniform subsidy rate on renewable energy;

positive variables
phi_ls  Lump-sum recycling
phi_tc  Consumption tax recycling;


equations

*       Zero profit conditions for activities linked to activity levels
zprf_roi        Zero profit condition for macro production sector
zprf_ele(t)     Zero profit condition for alternative electricity supply technologies
zprf_s(ff)      Zero profit condition for fossil fuel supplies
zprf_c          Zero profit condition for aggregate utility formation
zprf_g          Zero profit condition for public good formation

*       Market clearance conditions for goods linked to prices
mkt_proi        Market clearance condition for macro production good
mkt_pele        Market clearance condition for electricity
mkt_pf(ff)      Market clearance condition for fossil fuels coal and gas
mkt_pl          Market clearance condition for labor
mkt_pk          Market clearance condition for malleable capital
mkt_pr(ff)      Market clearance conditions for fossil fuel resources
mkt_pn(n)       Market clearance conditions for natural resources
mkt_pcarb       Market clearance condition for carbon
mkt_pkx(t)      Market clearance condition for capital inputs to extant power production
mkt_plim(t)     Market clearance condition for capacity on electricity expansion
mkt_pc          Market clearance for aggregate utility good
mkt_g           Market clearance for public good

*       Income balance for representative household linked to income level
inc_ra          Budget constraint for representative household
inc_govt        Budget constraint for government

*       Additional constraints
sub_res         Endogenous subsidy to achieve renewable energy quota
eqy_ls          Equal yield constraint for lump-sum recycling
eqy_tc          Equal yield constraint for consumption tax recycling

parameter
theta_l_roi      Cost share of labor in ROI production
theta_ele_roi    Cost share of electricity in capital-electricity composite of ROI
```

```
theta_r_ff(ff)   Cost share of fossil fuel resource in fossil fuel production
theta_l_ff(ff)   Cost share of labor in non-resource input of fossil fuel production
theta_roi_ff(ff) Cost share of ROI in ROI-labor composite of fossil fuel production
theta_ele_c      Cost share of electricity in oil-electricity composite of final consmption
theta_roi_c      Cost share of ROI in final consumption
theta_roi_t(t)   Cost share of ROI in electricity production by technology t
theta_k_t(t)     Cost share of capital in electricity production by technology t
theta_ff_t(ff,t) Cost share of fossil fuel in electricity production by technology t;

theta_roi_c     = -sam("roi","ra")/c0;
theta_l_roi     = (-sam("labor","roi"))/sam("roi","roi");
theta_ele_roi   = (-sam("ele","roi"))/ ((-sam("capital","roi")) + (-sam("ele","roi")));
theta_r_ff(ff)  = (-sam("rent",ff))/ ((-sam("rent",ff)) + (-sam("roi",ff)) + (-sam("labor",ff)));
theta_roi_ff(ff)= (-sam("roi",ff)) / ((-sam("roi",ff)) + (-sam("labor",ff)));
theta_ele_c     = (-sam("ele","ra"))/((-sam("ele","ra")) + (-sam("oil","ra")));
theta_roi_t(t)$xt(t)    = (-xtelec("roi",t)/xtelec("ele",t));
theta_k_t(t)$xt(t)      = (-xtelec("capital",t)/xtelec("ele",t));
theta_ff_t(ff,t)$xt(t)  = (-xtelec(ff,t)/xtelec("ele",t));
theta_roi_t(t)$nt(t)    = (-ntelec("roi",t)/ntelec("ele",t));
theta_k_t(t)$nt(t)      = (-ntelec("capital",t)/ntelec("ele",t));
theta_l_ff(ff)          = (-sam("labor",ff))/((-sam("labor",ff))+(-sam("roi",ff)));

*       Definition of zero profit conditions
zprf_roi..
    (theta_l_roi*pl**(1-esub_l_ke) + (1- theta_l_roi)
    *(theta_ele_roi*pele**(1-esub_k_e) + (1-theta_ele_roi)*pk**(1-esub_k_e))
    **((1-esub_l_ke)/(1-esub_k_e)))**(1/(1-esub_l_ke))
                =G= proi;

zprf_ele(t)..
    {theta_roi_t(t)*proi+ sum(ff,theta_ff_t(ff,t)*pf(ff))
     + (theta_k_t(t)*pkx(t))$shortrun
     + (theta_k_t(t)*pk)$(not shortrun)
     +  plim(t)$limit(t)
    }$xt(t)
    +
    {theta_roi_t(t)*proi + theta_k_t(t)*pk + sum(n, (-ntelec(n,t))*pn(n))}$nt(t)
             =G= pele*(1+tau$quota(t));

zprf_s(ff)..
    (theta_r_ff(ff)*pr(ff)**(1-esub_ff(ff)) +  (1-theta_r_ff(ff))*( theta_l_ff(ff)*pl
     + (1-theta_l_ff(ff))*proi)**(1-esub_ff(ff)))**(1/(1-esub_ff(ff)))
     + ((carbon(ff)*pcarb))$carblim
```

```
            =G= pf(ff);

zprf_c..
    (theta_roi_c*((proi*(1+tc0*phi_tc$dd))/(1+tc0$dd))**(1-esub_c)
     + (1-theta_roi_c)*(theta_ele_c*pele**(1-esub_ele)
     +(1-theta_ele_c)*pf("oil")**(1-esub_ele))**((1-esub_c)/(1-esub_ele)))**(1/(1-esub_c))
           =G= pc;

zprf_g$dd..
    proi =G= pg;

*       Definition of market clearance conditions
mkt_proi..
        roi*sam("roi","roi")  =G=
        sum(xt, ele(xt)*(-xtelec("roi",xt)/xtelec("ele",xt)))
        + sum(nt, ele(nt)*(-ntelec("roi",nt)))
        + sum(ff, (-sam("roi",ff))*s(ff)* ((theta_r_ff(ff)*pr(ff)**(1-esub_ff(ff))
        +  (1-theta_r_ff(ff))*( theta_l_ff(ff)*pl
        + (1-theta_l_ff(ff))*proi)**(1-esub_ff(ff)))**(1/(1-esub_ff(ff)))
        /( theta_l_ff(ff)*pl  + (1-theta_l_ff(ff))*proi))**esub_ff(ff))
        + (-sam("roi","ra")/(1+tc0$dd))*c*( (pc/(proi*(1+(tc0*phi_tc)$dd)))*(1+tc0$dd))**esub_c
        + (g0*g)$dd;

mkt_pele..
        sum(t, ele(t))  =G=
       (-sam("ele","ra"))*c*(pc/(theta_ele_c*pele**(1-esub_ele)
       +(1-theta_ele_c)*pf("oil")**(1-esub_ele))**(1/(1-esub_ele)))**esub_c
       * (((theta_ele_c*pele**(1-esub_ele)
       +(1-theta_ele_c)*pf("oil")**(1-esub_ele))**(1/(1-esub_ele)))/pele)**esub_ele
       + (-sam("ele","roi"))*roi*(proi/((theta_ele_roi*pele**(1-esub_k_e)
       + (1-theta_ele_roi)*pk**(1-esub_k_e))**(1/(1-esub_k_e))))**esub_l_ke
       *((theta_ele_roi*pele**(1-esub_k_e)
       + (1-theta_ele_roi)*pk**(1-esub_k_e))**(1/(1-esub_k_e))/pele)**esub_k_e;

mkt_pf(ff)..
       sam(ff,ff)*s(ff) =G=
       sum(xt, (-xtelec(ff,xt)/xtelec("ele",xt))*ele(xt))
       + (-sam(ff,"ra"))*c*(pc/(theta_ele_c*pele**(1-esub_ele)
       +(1-theta_ele_c)*pf("oil")**(1-esub_ele))**(1/(1-esub_ele)))**esub_c
       * (((theta_ele_c*pele**(1-esub_ele)
       +(1-theta_ele_c)*pf("oil")**(1-esub_ele))**(1/(1-esub_ele)))/pf("oil"))**esub_ele;

mkt_pl..
```

```
       sam("labor","ra") =G=
       (-sam("labor","roi"))*roi*(proi/pl)**esub_l_ke
       + sum(ff, (-sam("labor",ff))*s(ff)* ((theta_r_ff(ff)*pr(ff)**(1-esub_ff(ff))
       +  (1-theta_r_ff(ff))*( theta_l_ff(ff)*pl
       + (1-theta_l_ff(ff))*proi)**(1-esub_ff(ff)))**(1/(1-esub_ff(ff)))
       /( theta_l_ff(ff)*pl  + (1-theta_l_ff(ff))*proi))**esub_ff(ff));

mkt_pk..
      (-sam("capital","roi")+sum(xt,(-xtelec("capital",xt)))$(not shortrun)) =G=
      (-sam("capital","roi"))*roi*(proi/((theta_ele_roi*pele**(1-esub_k_e)
      + (1-theta_ele_roi)*pk**(1-esub_k_e))**(1/(1-esub_k_e))))**esub_l_ke
      *((theta_ele_roi*pele**(1-esub_k_e)
      + (1-theta_ele_roi)*pk**(1-esub_k_e))**(1/(1-esub_k_e))/pk)**esub_k_e
      + sum(xt$(not shortrun),(-xtelec("capital",xt)/xtelec("ele",xt))*ele(xt))
      + sum(nt,(-ntelec("capital",nt))*ele(nt));

mkt_pr(ff)..
      (-sam("rent",ff)) =G=
      (-sam("rent",ff))*s(ff)* ((theta_r_ff(ff)*pr(ff)**(1-esub_ff(ff))
      +  (1-theta_r_ff(ff))*( theta_l_ff(ff)*pl
      + (1-theta_l_ff(ff))*proi)**(1-esub_ff(ff)))**(1/(1-esub_ff(ff)))/pr(ff))** esub_ff(ff);

mkt_pn(n)..
      nrsupply(n) =G= sum(nt,(-ntelec(n,nt))*ele(nt));

mkt_pkx(xt)$shortrun..
      (-xtelec("capital",xt)) =G= (-xtelec("capital",xt)/xtelec("ele",xt))*ele(xt);

mkt_plim(xt)$limit(xt)..
      limit(xt) =G= ele(xt);

mkt_pcarb$carblim..
      carblim =G= sum(ff,(carbon(ff)*sam(ff,ff))*s(ff));

mkt_pc ..
      c0*c =G= ra/pc ;

mkt_g$dd ..
     g0*g =G= govt/pg ;

*       Income definition for representative household
inc_ra..
    (-sam("capital","roi")+sum(xt,(-xtelec("capital",xt)))$(not shortrun))*pk
```

```
    + sum(xt$shortrun, (-xtelec("capital",xt))*pkx(xt))
    + sam("labor","ra")*pl
    + sum(ff,(-sam("rent",ff))*pr(ff))
    + sum(n, nrsupply(n)*pn(n))
    + (carblim*pcarb)$carblim$(not dd)
    + sum(xt$limit(xt), limit(xt)*plim(xt))
    - sum(t$quota(t), pele*ele(t)*tau)
    - (pc*phi_ls)$dd
    =G=  ra;

*       Income definition for government
inc_govt$dd..
    (carblim*pcarb)$carblim + pc*phi_ls
    + ((-sam("roi","ra")/(1+tc0$dd))*c
    *( (pc/(proi*(1+(tc0*phi_tc)$dd)))*(1+tc0$dd))**esub_c)*proi*tc0*phi_tc
    =G= govt;

*       Endogenous subsidy to assure renewables quota
sub_res$card(quota)..
    sum(t$res(t), ele(t)) =G= share*sum(t, ele(t));

*       Endogenous equal yield constraints
eqy_ls$dd..
     g =G= 1;

eqy_tc$dd..
     g =G= 1;


*       Define MCP model
model mcp_hybrid / zprf_roi.roi, zprf_ele.ele, zprf_s.s, zprf_c.c, zprf_g.g,
                mkt_proi.proi, mkt_pele.pele, mkt_pf.pf, mkt_pl.pl,
                mkt_pk.pk, mkt_pr.pr, mkt_pn.pn, mkt_pcarb.pcarb,
                mkt_pkx.pkx, mkt_plim.plim, mkt_pc.pc, mkt_g.pg, inc_ra.ra,
                sub_res.tau, inc_govt.govt, eqy_ls.phi_ls, eqy_tc.phi_tc
                /;

*       Benchmark initialization

*       In the base year new-vintage technologies are inactive
*       and the prices of backstop natural resources are zero
*       Extant technologies with capacity limits are assumed to
*       operate at the upper bound with a zero shadow value in the
```

```
*       base year

ele.l(nt)  = 0;
pn.l(n)    = 0;
plim.l(xt) = 0;

ele.l(xt)  = xtelec("ele",xt);

*       Initialize activities and prices
roi.l = 1; ele.l(xt)= xtelec("ele",xt);  s.l(ff) = 1; c.l = 1;
proi.l = 1; pele.l = 1; pf.l(ff) = 1; pl.l = 1; pk.l = 1; pr.l(ff) = 1;
pkx.l(t)$((-xtelec("capital",t))$shortrun) = 1; plim.l(t) = 0;
pn.l(n) = 1; pc.l = 1;

*       Install lower bounds on prices to avoid divison by zero in MCP formulation
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; pkx.lo(t)$((-xtelec("capital",t))$shortrun) = 1e-5; pc.lo = 1e-5;

*       Tie down "active" model specification
phi_tc.fx = 1; phi_ls.fx = 0;
g.fx = 0; pg.fx = 0; govt.fx = 0; pcarb.fx = 0;
pkx.fx(t)$(not (-xtelec("capital",t))$shortrun) = 0;
tau.fx$(not card(quota)) = 0;
plim.fx(t)$(not limit(t)) = 0;

*       In the base year we have no new-vintage electricity and the prices of backstop
*       natural resources are zero:

ele.l(nt)       = 0;
pn.l(n)         = 0;
pcarb.l         = 0;
pkx.l(t)$((-xtelec("capital",t))$shortrun) =1;

ra.l =     (-sam("capital","roi")+sum(xt,(-xtelec("capital",xt)))$(not shortrun))*pk.l
                + sum(xt$shortrun, (-xtelec("capital",xt))*pkx.l(xt))
                + sam("labor","ra")*pl.l
                + sum(ff,(-sam("rent",ff))*pr.l(ff))
                + sum(n, nrsupply(n)*pn.l(n))
                + (carblim*pcarb.l)$carblim
                + sum(xt$limit(xt), limit(xt)*plim.l(xt))
                - sum(t$quota(t), pele.l*ele.l(t)*tau.l)
                - (pc.l*phi_ls.l)$dd;

```

```
govt.l$dd =    (carblim*pcarb.l)$carblim + pc.l*phi_ls.l
                + (-sam("roi","ra")/(1+tc0$dd))*c.l*(pc.l/(proi.l*(1+tc0*phi_tc.l)$dd)
                  /(1+tc0$dd))**esub_c*pc.l*tc0*phi_tc.l;

*       Check the benchmark:
*       - marginal of all active activities must be zero
*       - marginal of all positivie prices must be zero
*       - marginal of all positive incomens must be zero

mcp_hybrid.iterlim = 0;
solve mcp_hybrid using mcp;

*       Relax iteration limit for counterfactual policy analysis
mcp_hybrid.iterlim      = 4000;

*===========================================================================
*       Analysis of policy scenarios (as laid out in the paper)
*
*       (i)   gradual nuclear phase-out
*       (ii)  target quota for renewables (green quota)
*       (iii) carbon taxation (environmental tax reform)


*       Define report parameters
parameter
        ev(*)           Equivalent variation in income
        supply(*,*)     Electricity supply by technology
        carbtax(*)      Carbon permit price
        subsidy         Subsidy rate on electricity from renewables
        report          Report default parameter;

scalar epsilon /1.e-5/;

*===========================================================================
*       Scenario 1: Gradual nuclear phase-out

set     nsc  Nuclear phase scenarios / 0, 25, 50, 75, 100/;

parameter limit_0       Base year capacity limits;
limit_0("nuclear") = limit("nuclear");

loop(nsc,

```

```
*       Assign available capacity for nuclear power
        limit("nuclear") = (1 - (ord(nsc)-1)/(card(nsc)-1))*limit_0("nuclear");
Display limit;
*       If nuclear capacity is set to zero, assure complete nuclear phase out
        if ((not limit("nuclear")),
           ele.fx("nuclear") = 0;
           );
        solve mcp_hybrid using mcp;
        supply(nsc,t)       = ele.l(t)  + epsilon;
        ev(nsc)             = 100 * (c.l-1) + epsilon ;

);


$setglobal labels nsc
$setglobal gp_opt0 "set data style linespoints"

$setglobal gp_opt1 "set key below"
report(nsc,"ev") = ev(nsc);
$setglobal gp_opt2 "set title ’Welfare changes’"
$setglobal gp_opt3 "set xlabel ’Nuclear capacity reduction (% vis--vis BaU)’"
$setglobal gp_opt4 "set ylabel ’Equivalent variation in income (%)’"
$libinclude plot report
display report;
report(nsc,"ev") = 0;

$setglobal gp_opt2 "set title ’Electricity supply by technology’"
$setglobal gp_opt3 "set xlabel ’Nuclear capacity reduction (% vis--vis BaU)’"
$setglobal gp_opt4 "set ylabel ’Activity level of technologies’"
$libinclude plot supply

*       Re-initialize parameterization for subsequent scenarios
limit("nuclear") = limit_0("nuclear");
ele.lo("nuclear") = 0; ele.up("nuclear") = +inf; ele.l("nuclear")=xtelec("ele","nuclear");


*===========================================================================
*       Scenario 2: Green quotas

set     qsc  Green quota scenarios / 0 13, 5 18, 10 23, 15 28, 20 33/;
*       Note:   We start from the base year situation without binding target
*               share and then increase the share iteratively by 5%.
*               The descriptive text for scenario set elements captures
```

```
*               the actual target level of green electricity as percent
*               in overall electricity production (base year quota is 13%).
*               The plot-command picks up the descriptive text as
*               scenario labels when produce a graphical exposition of results.

*       Assign initial level values for variables
roi.l = 1; ele.l(xt)= xtelec("ele",xt);  s.l(ff) = 1; c.l = 1;
proi.l = 1; pele.l = 1; pf.l(ff) = 1; pl.l = 1; pk.l = 1; pr.l(ff) = 1;
pkx.l(t)$((-xtelec("capital",t))$shortrun) = 1; plim.l(t) = 0;
pn.l(n) = 1; pc.l = 1;
*       Install lower bounds on prices to avoid divison by zero in MCP formulation
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;
pkx.lo(t)$((-xtelec("capital",t))$shortrun) = 1e-5; pc.lo = 1e-5;
ra.l = c0;

parameter share_0       Base year renewable share;
share_0 = share;

quota(res) = yes;
tau.lo = 0; tau.l = 0; tau.up = 0.99;

loop(qsc,
*       Assign target shares for renewables in electricity production
        share  = min(1, (share_0 + 20/100* (ord(qsc)-1)/(card(qsc)-1)));

        solve mcp_hybrid using mcp;

        supply(qsc,t)   = ele.l(t)  + epsilon;
        ev(qsc)         = 100 * (c.l-1) + epsilon;
        subsidy(qsc)    = 100*tau.l + epsilon;
);

$setglobal labels qsc

report(qsc,"ev") = ev(qsc);
$setglobal gp_opt2 "set title 'Welfare changes'"
$setglobal gp_opt3 "set xlabel 'Green quota in % of overall electricity supply'"
$setglobal gp_opt4 "set ylabel 'Equivalent variation in income (%)'"
$libinclude plot report
display report;
report(qsc,"ev") = 0;

$setglobal gp_opt2 "set title 'Electricity supply by technology'"
```

```
$setglobal gp_opt3 "set xlabel 'Green quota in % of overall electricity supply'"
$setglobal gp_opt4 "set ylabel 'Activity level of technologies'"
$libinclude plot supply

report(qsc,"subsidy") = subsidy(qsc);
$setglobal gp_opt2 "set title 'Subsidy on renewables'"
$setglobal gp_opt3 "set xlabel 'Green quota in % of overall electricity supply'"
$setglobal gp_opt4 "set ylabel 'Subsidy rate (% of electricity price)'"
$libinclude plot report
display report;
report(qsc,"subsidy") = 0;

*       Re-initialize parameterization for subsequent scenarios
share = share_0;
quota(res) = no;
tau.fx = 0;
*===========================================================================
*       Scenario 3: Carbon taxation (double dividend)

*       First re-specify base year (benchmark) to public good extension
mcp_hybrid.iterlim      = 0;

dd  = 1;
g.lo = 0; g.up = + inf; govt.lo = 0; govt.up = + inf;
g0  = 0.2 *(-sam("roi","ra"));
tc0 = g0/((-sam("roi","ra")) - g0);
display g0, tc0;

*       Relax ficed variables
g.lo = 0; g.up = +inf;  pg.lo = 0; pg.up = +inf; govt.lo = 0; govt.up = + inf;
pcarb.lo = 0; pcarb.up = + inf;

*       Initially, we assume that lump-sum transfers are active
*       as the equal-yield instrument
phi_ls.l  = 0; phi_ls.lo = -inf; phi_ls.up = +inf;
phi_tc.fx = 1;

*       Assign base year carbon emissions (at shadow price of zero)
carblim = sum(ff, sam(ff,ff)*carbon(ff));
pcarb.l = 0;

*       Benchmark replication check for the model with public good extension
*       Initialize activities and prices
```

```
roi.l = 1; ele.l(xt)= xtelec("ele",xt);  ele.l(nt) = 0; s.l(ff) = 1; c.l = 1;
proi.l = 1; pele.l = 1; pf.l(ff) = 1; pl.l = 1; pk.l = 1; pr.l(ff) = 1; pg.l = 1;
pkx.l(t)$((-xtelec("capital",t))$shortrun) = 1; plim.l(t)$limit(t) = 0;
pc.l = 1; pn.l(n) = 0; ra.l = c0; govt.l = g0;

*       Install lower bounds on prices to avoid divison by zero in MCP formulation
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;
pkx.lo(t)$((-xtelec("capital",t))$shortrun) = 1e-5; pc.lo = 1e-5; pg.lo = 1e-5;

*       Check the re-specified benchmark:
*       - marginal of all active activities must be zero
*       - marginal of all positivie prices must be zero
*       - marginal of all positive incomens must be zero

mcp_hybrid.iterlim = 0;

solve mcp_hybrid using mcp;

*       Relax iteration limit
mcp_hybrid.iterlim = 4000;


*       Specification of carbon tax scenarios based on exogenous emission reduction targets
set     csc  Carbon abatement scenarios scenarios / 0, 5, 10, 15, 20/;

parameter carbon_0      Benchmark capacity limits;
parameter ev_           Report parameter for welfare changes;

carbon_0 = carblim;

display carbon_0;

loop(csc,
*       Assign carbon emission limit
        carblim = (1 - 0.2*(ord(csc)-1)/(card(csc)-1))*carbon_0;

*       Activate lump-sum transfer as recycling instrument
phi_ls.l  = 0; phi_ls.lo = -inf; phi_ls.up = +inf;
phi_tc.fx = 1;

        solve mcp_hybrid using mcp;

        ev_(csc,"ls")           = 100 * (c.l-1) + epsilon;
```

```

*       Activate consumption tax as recycling instrument
phi_tc.l = 1; phi_tc.lo = -0.99;  phi_tc.up = +inf;
phi_ls.fx  = 0;
        solve mcp_hybrid using mcp;

        ev_(csc,"tc")           = 100 * (c.l-1) + epsilon;
);

$setglobal labels csc
$setglobal gp_opt2 "set title ’Welfare changes’"
$setglobal gp_opt3 "set xlabel ’Carbon emission reduction (in % vis--vis base year)’"
$setglobal gp_opt4 "set ylabel ’Equivalent variation in income (%)’"
$libinclude plot ev_
display ev_;
ev_(csc,"tc") = 0; ev_(csc,"ls") = 0;

*       Re-initialize parameterization for subsequent policy scenarios
dd = 0; g0 = 0; tc0 = 0;
```

5.2 MPSGE Formulation

```
$Title  Static maquette of integrated TD/BU hybrid model

*       Model formulation in meta-language MPSGE
*       (see Rutherford 1995 for documentation)

*===========================================================================
* Model code for stylzed integrated bottom-up/top-down analysis of energy
* policies based on:
*
*               ZEW Discussion Paper 05-28
*          Integrating Bottom-Up into Top-Down:
*            A Mixed Complementarity Approach
*
* Contact the authors at: boehringer@zew.de; rutherford@colorado.edu
*============================================================================

* For plotting the results you must have installed the gnuplot-shareware
* (see http://debreu.colorado.edu/gnuplot/gnuplot.htm for downloads)

*============================================================================
*       List of parameters subject to sensitivity analysis
*       The user can change the default settings.

* Choice of key elasticities:
*       Elasticity of substitution in final consumption
$if not setglobal esub_c $setglobal esub_c 0.5

*       Elasticity in gas supply
$if not setglobal esub_gas  $setglobal esub_gas  1.5

*       Elasticity in coal supply
$if not setglobal esub_coal  $setglobal esub_coal 3

*       Elasticity in oil supply
$if not setglobal esub_oil  $setglobal esub_oil 1.5


* Choice of resource availability for renewables:
* (as a fraction of base-year total electricity production)
*       Potential wind supply - (%)
$if not setglobal p_wind  $setglobal p_wind  10
```

```

*       Potential solar supply - (%)
$if not setglobal p_sun  $setglobal p_sun   10

*       Potential biomass supply - (%)
$if not setglobal p_trees  $setglobal p_trees 10


* Cost disadvantage of inital slack technologies:
*       Wind energy premium (%)
$if not setglobal c_wind  $setglobal c_wind 10

*       Solar energy premium (%)
$if not setglobal c_solar  $setglobal c_solar   10

*       Biomass energy premium (%)
$if not setglobal c_biomass  $setglobal c_biomass 10


* Other central model assumptions:
*       Time horizon (short, long)
*       N.B.: For short-run analysis capital is immobile across sectors
$if not setglobal horizon  $setglobal horizon long

*============================================================================


*       Assign user-specific changes of default assumptions
scalar  shortrun        Flag for short-run capital mobility/1/;

$if "%horizon%"=="long" shortrun=0;

*       Elasticitities of substitution (ESUB)
scalar  esub_c     Elasticity of substituion in final demand /%esub_c%/
        esub_ele   ESUB between electricity and oil in final demand /0.5/
        esub_k_e   ESUB between capital and energy in ROI production /0.5/
        esub_l_ke  ESUB between labor and other inputs in ROI production /0.8/;

set     t       Electricity Technologies (current and future)
                /coal,gas,nuclear,hydro,wind,solar,biomass/;

set     xt(t)   Existing technologies /coal,gas,nuclear,hydro/;

```

```
set     nt(t)   New vintage technologies /wind,solar,biomass/;

set     ff      Fossil fuel inputs /coa, gas, oil/;

set     n       Natural resources /wind, sun, trees/;


set     res(t)  Renewable energy sources /hydro, wind, solar, biomass/;

*       The following data table describes an economic equilibrium in
*       the base year:


table sam  Base year social accounting matrix

        roi     coa     gas     oil     ele     ra
roi     200     -5      -5      -10     -10    -170
coa             15                      -15
gas                     15              -15
oil                             30              -30
ele     -10                              60     -50
capital -80                             -20     100
labor   -110    -5      -5      -10             130
rent            -5      -5      -10              20             ;

parameter carbon(ff)    Carbon coefficients /oil 1, gas 1, coa 2/;

scalar  carblim         Carbon target /0/;

parameter  esub_ff(ff)  Elastictity of substitution in fossil fuel production
        /gas %esub_gas%, coa %esub_coal%, oil %esub_oil%/;

*       The following data tables describes electricy generation in
*       the base year as well as the technology coefficients for technologies
*       which are inactive in the base year (wind, solar, biomass). Inactive
*       technologies are by defaults %c_****% more costly.

table xtelec  Electricty technologies - extant (initially active)

        coal    gas     nuclear hydro
ele       20     20          12     8
roi       -1     -1          -8
gas             -15
```

```
coa      -15
capital   -4     -4          -4    -8;


table ntelec  Electricty technologies - new vintage (initially inactive)

         wind    solar   biomass
ele       1.0      1.0      1.0
roi       -.2      -.3      -.4
capital   -.9      -.8      -.7
wind     -1.0
sun               -1.0
trees                      -1.0;


*       Adjust the cost coefficients for initially inactive technologies
*       according to user assumptions:
set xk /roi, capital/;

ntelec(xk,"wind")    = ntelec(xk,"wind")    * (100+%c_wind%)/110;
ntelec(xk,"solar")   = ntelec(xk,"solar")   * (100+%c_solar%)/110;
ntelec(xk,"biomass") = ntelec(xk,"biomass") * (100+%c_biomass%)/110;


*       Specify limits (resource or policy constraints) to the availability
*       of technologies

parameter limit    Electricty supply limits on extant technologies /
        nuclear         12
        hydro            8 /;

parameter  nrsupply(n)  Natural resource supplies (fraction of base output)/
        wind            %p_wind%
        sun             %p_sun%
        trees           %p_trees% /;

nrsupply(n) = nrsupply(n)/100 * sam("ele","ele");

parameter c0    Baseyear final consumption;
c0 = (-sam("roi","ra")-sam("ele","ra")-sam("oil","ra"));


set     quota(t)  Flag for technologies contributing to green quota;
```

```
quota(t) = no;

scalar  share   Target share for green quota /0/;

*       By default we might set target share for green quota at base year level
share = sum(t$res(t), xtelec("ele",t))/sum(t, xtelec("ele",t));
display share;

scalar
        dd      Flag for double dividend policy analysis /0/,
        ls      Flag for lump-sum revenue-recyling       /0/,
        vat     Flag for VAT revenue recycling           /0/,
        g0      Base year public consumption             /0/,
        tc0     Base year consumption tax                /0/;

*       MPSGE formulation of the hybrid model
$ontext

$model:mps_hybrid

$sectors:
        roi     ! Aggregate output
        ele(t)  ! Production levels for electricity by technology
        s(ff)   ! Fossil fuel supplies
        c       ! Aggregate consumption (utility) formation
        g$dd    ! Public good provision

$commodities:
        proi    ! Price of aggregate output
        pele    ! Price of electricty
        pf(ff)  ! Price of oil and gas
        pl      ! Wage rate
        pk      ! Price of malleable capital for X (and NT elec)
        pr(ff)  ! Rent on fossil fuel resources
        pn(n)   ! Rent on natural resources
        pc      ! Consumption (utility) price index
        pg$dd   ! Price of public consumption
        plim(t)$limit(t)                         ! Shadow price on electricity expansion
        pkx(t)$((-xtelec("capital",t))$shortrun) ! Price of capital to extant technologies
        pcarb$carblim                            ! Carbon tax rate

$consumers:
        ra      ! Representative household
```

```
        govt$dd ! Government

$auxiliary:
        tau$card(quota)  ! Uniform subsidy rate on renewable energy
        phi_ls$dd        ! Lump-sum recycling
        phi_tc$dd        ! Consumption tax recycling


*       Aggregate output:

$prod:roi s:esub_l_ke ke:esub_k_e
        o:proi  q:sam("roi","roi")
        i:pl    q:(-sam("labor","roi"))
        i:pk    q:(-sam("capital","roi"))  ke:
        i:pele  q:(-sam("ele","roi"))      ke:

*       Extant electricity:

$prod:ele(xt)
        o:pele               q:1   raa:ra   n:tau$quota(xt)     m:(-1)$quota(xt)
        i:proi               q:(-xtelec("roi",xt)/xtelec("ele",xt))
        i:pf(ff)             q:(-xtelec(ff,xt)/xtelec("ele",xt))
        i:pkx(xt)$shortrun   q:(-xtelec("capital",xt)/xtelec("ele",xt))
        i:pk$(not shortrun)  q:(-xtelec("capital",xt)/xtelec("ele",xt))
        i:plim(xt)$limit(xt) q:1

*       New vintage electricity:

$prod:ele(nt)
        o:pele  q:1     a:ra   n:tau$quota(nt)  m:(-1)$quota(nt)
        i:proi  q:(-ntelec("roi",nt))
        i:pk    q:(-ntelec("capital",nt))
        i:pn(n) q:(-ntelec(n,nt))

$prod:s(ff) s:0  r:esub_ff(ff)   xl(r):0
        o:pf(ff)        q:sam(ff,ff)
        i:pcarb$carblim q:(carbon(ff)*sam(ff,ff))
        i:proi          q:(-sam("roi",ff))      xl:
        i:pl            q:(-sam("labor",ff))    xl:
        i:pr(ff)        q:(-sam("rent",ff))     r:

$prod:c s:esub_c e:esub_ele
        o:pc            q:c0
```

```
        i:proi          q:(-sam("roi","ra")/(1+tc0$dd)) p:(1+tc0$dd)
+ a:govt$dd n:phi_tc$dd  m:tc0$dd
        i:pele          q:(-sam("ele","ra"))    e:
        i:pf("oil")     q:(-sam("oil","ra"))    e:

$demand:ra
        d:pc                      q:c0
        e:pk    q:(-sam("capital","roi")+sum(xt,(-xtelec("capital",xt)))$(not shortrun))
        e:pkx(xt)$shortrun        q:(-xtelec("capital",xt))
        e:pl                      q:(sam("labor","ra"))
        e:pr(ff)                  q:(-sam("rent",ff))
        e:pn(n)                   q:nrsupply(n)
        e:pcarb$carblim$(not dd)  q:carblim
        e:plim(xt)$limit(xt)      q:limit(xt)
        e:pc$dd                   q:(-1)        r:phi_ls$dd


$demand:govt$dd
        d:pg    q:g0
        e:pc    q:1             r:phi_ls
        e:pcarb$carblim         q:carblim

$prod:g$dd
        O:pg    q:g0
        i:proi  q:g0


$constraint:tau$card(quota)
        sum(t$res(t), ele(t)) =e= share*sum(t, ele(t));


$constraint:phi_ls$dd
        g =e= 1;

$constraint:phi_tc$dd
        g=e= 1;

$offtext
$sysinclude mpsgeset mps_hybrid

*       In the base year new-vintage technologies are inactive
*       and the prices of backstop natural resources are zero
*       Extant technologies with capacity limits are assumed to
```

```
*       operate at the upper bound with a zero shadow value in the
*       base year

ele.l(nt)  = 0;
pn.l(n)    = 0;
plim.l(xt) = 0;

ele.l(xt)  = xtelec("ele",xt);

*       Benchmark replication check
mps_hybrid.iterlim = 0;
$include mps_hybrid.gen
solve mps_hybrid using mcp;

display "The precision of the benchmark dataset is:", mps_hybrid.objval;
abort$(ABS(mps_hybrid.objval) gt 1e-4)"MPSGE model does not calibrate";


*       Relax iteration limit for counterfactual policy analysis
mps_hybrid.iterlim      = 4000;


*===========================================================================
*       Analysis of policy scenarios (as laid out in the paper)
*
*       (i)   gradual nuclear phase-out
*       (ii)  target quota for renewables (green quota)
*       (iii) carbon taxation (environmental tax reform)


*       Define report parameters
parameter
        ev(*)           Equivalent variation in income
        supply(*,*)     Electricity supply by technology
        carbtax(*)      Carbon permit price
        subsidy         Subsidy rate on electricity from renewables
        report          Report default parameter;

scalar epsilon /1.e-5/;


*===========================================================================
*       Scenario 1: Gradual nuclear phase-out
```

```

set     nsc  Nuclear phase scenarios / 0, 25, 50, 75, 100/;

parameter limit_0       Base year capacity limits;
limit_0("nuclear") = limit("nuclear");

loop(nsc,

*       Assign available capacity for nuclear power
        limit("nuclear") = (1 - (ord(nsc)-1)/(card(nsc)-1))*limit_0("nuclear");
*       If nuclear capacity is set to zero, assure complete nuclear phase out
        if ((not limit("nuclear")),
           ele.fx("nuclear") = 0;
           );
$include mps_hybrid.gen
        solve mps_hybrid using mcp;
        supply(nsc,t)       = ele.l(t)  + epsilon;
        ev(nsc)             = 100 * (c.l-1) + epsilon ;

);


$setglobal labels nsc
$setglobal gp_opt0 "set data style linespoints"

$setglobal gp_opt1 "set key below"
report(nsc,"ev") = ev(nsc);
$setglobal gp_opt2 "set title 'Welfare changes'"
$setglobal gp_opt3 "set xlabel 'Nuclear capacity reduction (% vis--vis BaU)'"
$setglobal gp_opt4 "set ylabel 'Equivalent variation in income (%)'"
$libinclude plot report
display report;
report(nsc,"ev") = 0;


$setglobal gp_opt2 "set title 'Electricity supply by technology'"
$setglobal gp_opt3 "set xlabel 'Nuclear capacity reduction (% vis--vis BaU)'"
$setglobal gp_opt4 "set ylabel 'Activity level of technologies'"
$libinclude plot supply

*       Re-initialize parameterization for subsequent scenarios
limit("nuclear") = limit_0("nuclear");
ele.lo("nuclear") = 0; ele.up("nuclear") = +inf;
```

```
ele.l("nuclear")=xtelec("ele","nuclear");


*===========================================================================
*       Scenario 2: Green quotas

set     qsc  Green quota scenarios / 0 13, 5 18, 10 23, 15 28, 20 33/;
*       Note:   We start from the base year situation without binding target
*               share and then increase the share iteratively by 5%.
*               The descriptive text for scenario set elements captures
*               the actual target level of green electricity as percent
*               in overall electricity production (base year quota is 13%).
*               The plot-command picks up the descriptive text as
*               scenario labels when produce a graphical exposition of results.


parameter share_0       Base year renewable share;
share_0 = share;

quota(res) = yes;


loop(qsc,
*       Assign target shares for renewables in electricity production
        share  = min(1, (share_0 + 20/100* (ord(qsc)-1)/(card(qsc)-1)));

$include mps_hybrid.gen
        solve mps_hybrid using mcp;

        supply(qsc,t)   = ele.l(t)  + epsilon;
        ev(qsc)         = 100 * (c.l-1) + epsilon;
        subsidy(qsc)    = 100*tau.l + epsilon;
);

$setglobal labels qsc

report(qsc,"ev") = ev(qsc);
$setglobal gp_opt2 "set title 'Welfare changes'"
$setglobal gp_opt3 "set xlabel 'Green quota in % of overall electricity supply'"
$setglobal gp_opt4 "set ylabel 'Equivalent variation in income (%)'"
$libinclude plot report
display report;
report(qsc,"ev") = 0;
```

```

$setglobal gp_opt2 "set title ’Electricity supply by technology’"
$setglobal gp_opt3 "set xlabel ’Green quota in % of overall electricity supply’"
$setglobal gp_opt4 "set ylabel ’Activity level of technologies’"
$libinclude plot supply

report(qsc,"subsidy") = subsidy(qsc);
$setglobal gp_opt2 "set title ’Subsidy on renewables’"
$setglobal gp_opt3 "set xlabel ’Green quota in % of overall electricity supply’"
$setglobal gp_opt4 "set ylabel ’Subsidy rate (% of electricity price)’"
$libinclude plot report
display report;
report(qsc,"subsidy") = 0;

*       Re-initialize parameterization for subsequent scenarios
share = share_0;
quota(res) = no;
$exit
*===========================================================================
*       Scenario 3: Carbon taxation (double dividend)

*       First re-calibrate base year (benchmark) to public good extension
mps_hybrid.iterlim      = 0;

dd  = 1;
g0  = 0.2 *(-sam("roi","ra"));
tc0 = g0/((-sam("roi","ra")) - g0);
display g0, tc0;

*       Initially, we assume that lump-sum transfers are active
*       as the equal-yield instrument
phi_ls.l  = 0; phi_ls.lo = -inf; phi_ls.up = +inf;
phi_tc.fx = 1;

*       Assign base year carbon emissions (at shadow price of zero)
carblim = sum(ff, sam(ff,ff)*carbon(ff));
pcarb.l = 0;

*       Benchmark replication check for the model with public good extension
*       Initialize activities and prices
roi.l = 1; ele.l(xt)= xtelec("ele",xt);  ele.l(nt) = 0; s.l(ff) = 1; c.l = 1;
proi.l = 1; pele.l = 1; pf.l(ff) = 1; pl.l = 1; pk.l = 1; pr.l(ff) = 1;
pkx.l(t)$((-xtelec("capital",t))$shortrun) = 1; plim.l(t)$limit(t) = 0;
```

```
pc.l = 1; pn.l(n) = 0; ra.l = c0; govt.l = g0;

mps_hybrid.iterlim = 0;
$include mps_hybrid.gen
solve mps_hybrid using mcp;

display "The precision of the re-specified benchmark dataset is:", mps_hybrid.objval;
abort$(ABS(mps_hybrid.objval) gt 1e-4)"MPSGE model does not calibrate";

*       Relax iteration limit
mps_hybrid.iterlim = 4000;


*       Specification of carbon tax scenarios based on exogenous emission reduction targets
set     csc  Carbon abatement scenarios scenarios / 0, 5, 10, 15, 20/;

parameter carbon_0      Benchmark capacity limits;
parameter ev_           Report parameter for welfare changes;

carbon_0 = carblim;

display carbon_0;

loop(csc,
*       Assign carbon emission limit
        carblim = (1 - 0.2*(ord(csc)-1)/(card(csc)-1))*carbon_0;

*       Activate lump-sum transfer as recycling instrument
phi_ls.l  = 0; phi_ls.lo = -inf; phi_ls.up = +inf;
phi_tc.fx = 1;
$include mps_hybrid.gen
        solve mps_hybrid using mcp;
        ev_(csc,"ls")           = 100 * (c.l-1) + epsilon;

*       Activate consumption tax as recycling instrument
phi_tc.l = 1; phi_tc.lo = -0.99;  phi_tc.up = +inf;
phi_ls.fx  = 0;
$include mps_hybrid.gen
        solve mps_hybrid using mcp;
        ev_(csc,"tc")           = 100 * (c.l-1) + epsilon;
);

$setglobal labels csc
```

```
$setglobal gp_opt2 "set title ’Welfare changes’"
$setglobal gp_opt3 "set xlabel ’Carbon emission reduction (in % vis--vis base year)’"
$setglobal gp_opt4 "set ylabel ’Equivalent variation in income (%)’"
$libinclude plot ev_
display ev_;
ev_(csc,"tc") = 0; ev_(csc,"ls") = 0;

*       Re-initialize parameterization for subsequent policy scenarios
dd = 0; g0 = 0; tc0 = 0;
```