Modeling methodology

(Version of March 14, 2011)

1 Overview of the GEM-E3 model

The model we have used for quantitative assessments of different possible equilibrium paths is the computable general equilibrium (CGE) model GEM-E3.[1] The GEM-E3 model is a multi-region multi-sector model that covers the interactions between energy, economy, and environment. The design of the GEM-E3 model has been developed following four main guidelines:

1. Model design around a basic general equilibrium core in a modular way so that different modeling options, market regimes and closure rules are supported by the same model specification.
2. Fully flexible (endogenous) coefficients in production and in consumers' demand.
3. Calibration to a base year data set, incorporating detailed Social Accounting Matrices as statistically observed.
4. Dynamic mechanisms, through the accumulation of capital stock.

The GEM-E3 model starts from the same basic structure as the standard World Bank models[2]. Following the tradition of these models, GEM-E3 is built on the basis of a Social Accounting Matrix (Decaluwe, Martens and Monette 1987; Decaluwe and Martens 1988) and explicitly formulates demand and supply equilibrium. Technical coefficients in production and demand are flexible in the sense that producers can alternate the mix of production not only regarding the primary production factors but also the intermediate goods. Production is modeled through KLEM (capital, labor, energy and materials) production functions involving many factors (all intermediate products and two primary factors – capital and labor). At the same time, consumers can also endogenously decide the structure of their demand for goods and services. Their consumption mix is decided through a flexible expenditure system involving durable and non-durable goods. The specification of production and consumption follows the generalized Leontief type models[3] as initiated in the work of Jorgenson.

---

[1] The GEM-E3 model was initially built under the auspices of EC (DG-RTD) by a consortium involving ICCS-NTUA, BUES, ERASME, KUL, PSI and ZEW. It is presented in detail by Capros et al. 1999. The version of the GEM-E3 used in this study has been developed by ICCS-NTUA within the EC(DG-RTD) funded project 'MODELS'.
The model code is owned by the EU and we are not in a position to share it. An open source code for a CGE model is included in Löfgren, Harris and Robinson 2001).

[2] The World Bank type of models constitutes the bulk of equilibrium modeling experiences. This type of models is usually used for comparative statics exercises. These models however do not use full scale production functions but rather work on value added and its components to which they directly relate final demand.

[3] The generalized Leontief type model was first formulated empirically in the work of D. W. Jorgenson who introduced flexibility in the Leontief framework, using production functions such as the translog function. The

The model is not limited to comparative static evaluation of policies. It is recursive dynamic (see Babiker et al. 2009 for a discussion in view of climate policy). Its properties are mainly manifested through stock/flow relationships, technical progress, active population growth, capital accumulation and agents' (backward looking) expectations[4] and the Quest model used in (Conte et al. 2010).

The model is calibrated to a base year data set that comprises a full Social Accounting Matrix for each EU country that is built by combining input-output tables (as published by EUROSTAT) with national accounts data. Bilateral trade flows are also calibrated for each sector represented in the model, taking into account trade margins and transport costs. Consumption and investment are built around transition matrices linking consumption by purpose to demand for goods and investment by origin to investment by destination. The initial starting point of the model, therefore, includes a very detailed treatment of taxation and trade. Total demand (final and intermediate) in each country is optimally allocated between domestic and imported goods, under the hypothesis that these are considered as imperfect substitutes (the "Armington" assumption, see Armington 1969).

GEM-E3 explicitly considers market clearing mechanisms, and related price formation, in the economy, energy and environment markets. Following a micro-economic approach, it formulates the supply or demand behaviour of the economic agents regarding production, consumption, investment, employment and allocation of their financial assets. Prices are computed by the model as a result of supply and demand interactions in the markets.

By simultaneously representing all markets of an economy, the model is able to capture their multiple interactions providing insights into the factors determining the allocation of resources and distribution of incomes. Figure 1 provides a sketch of the different decision steps and transactions represented in the model. The version used in the current study covers the whole world aggregated to 37 regions (27 of which are the EU member states). In each region the economy is aggregated to 25 activities represented by one typical firm that operates within a perfect competition market regime. Regarding the power generation sector a bottom-up approach has been adopted enabling to discretely identify 8 power producing technologies. All regions are linked through endogenous bilateral trade flows of goods and services following Armington (1969). Household consumption and leisure are derived through utility maximisation. In addition to the voluntary unemployment (as this is captured by the choice for leisure) the model computes involuntary unemployment by adopting the efficiency wages approach originated by Shapiro and Stiglitz (1984).

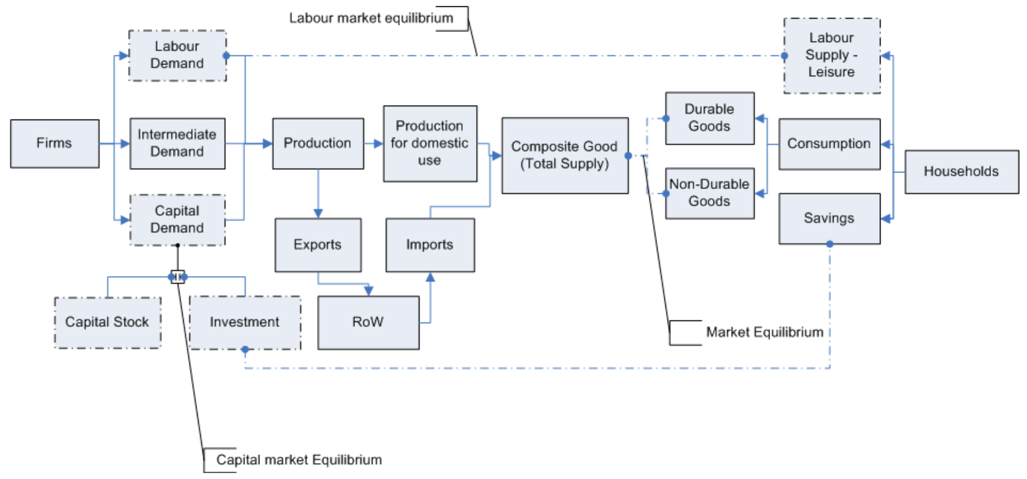
Institutional regimes, that affect agent behaviour and market clearing, are explicitly represented, including public finance, taxation and social policy. All common policy instruments affecting economy, energy and environment are included. The model is general and complete,

---

work of D. W. Jorgenson inspired many modeling efforts, in which particular emphasis has been put on energy. For example, such models have been developed in France by P. Capros and N. Ladoux, by the OECD (the GREEN and WALRAS models), in Sweden by L. Bergman and in Germany by K. Conrad.

[4] A recent generation of general equilibrium models involve rational expectations where the model is solved inter-temporally i.e. for all time-periods together. Recent examples of such models are the G-Cubed model (McKibbin and Wilcoxen 1995).

Figure 1: GEM-E3 Economic circuit



Source: E3M-Lab.

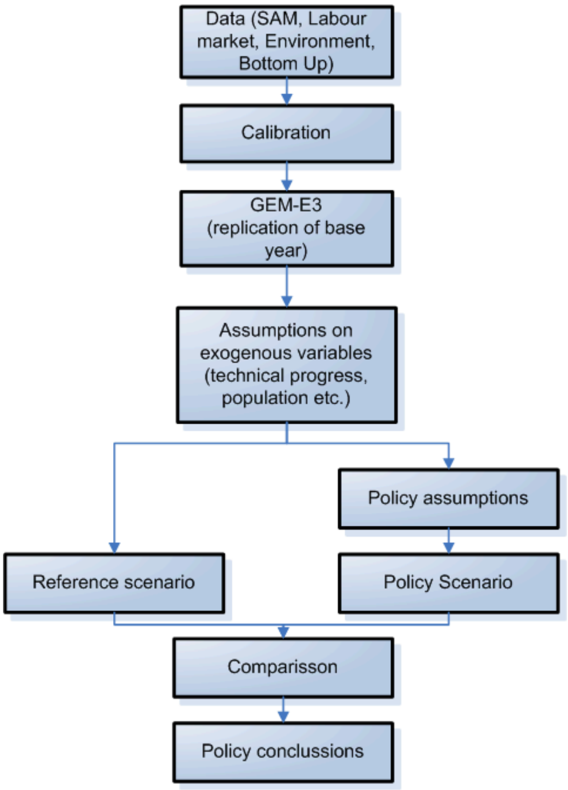
in the sense that it includes all agents, markets and geographic entities that affect European and World economic equilibrium. The model attempts also to represent goods that are external to the economy as for example damages to the environment.

The internalisation of environmental externalities is conveyed either through taxation or through global system constraints, the shadow costs of which affect the decisions of the economic agents. The current version of GEM-E3 links global constraints to environmental emissions, changes in consumption or production patterns, external costs/benefits, taxation, pollution abatement investments and pollution permits. It evaluates the impact of policy changes on the environment by calculating the change in atmospheric emissions and damages, and determines costs and benefits through an equivalent variation measurement of global welfare (inclusive environmental impact). The recent awareness about the greenhouse problem motivated the emergence of several empirical models for the analysis of economy-environment interactions. For example, the works of Nordhaus (2005); Jorgenson, Slesnick and Wilcoxen (1992); Manne and Richels (1997); Proost and Van Regemorter (1992) have focused on the economic conditions for obtaining CO_2 emission reductions by means of a carbon-related tax. Such a policy issue needs to be addressed by ensuring consistent representation of the interactions between the economy, the energy system and the emissions of CO_2.

The recursive dynamic model extends up to 2030 with a five year time step. The main drivers of economic growth, technical progress, agents' expectations and active population are assumed exogenous in the model. These exogenous variables are calibrated so as to produce a reference projection that is consistent with official economic and demographic projections (Brown et al. 2009; European Commission (DG ECFIN) and the Economic Policy Committee (AWG) 2009). Thus the analysis with the GEM-E3 model starts by constructing a reference projection of economic growth for the 37 regions with which the world is represented in the model. The reference projection, named baseline scenario, serves as a basis of comparison for the policy scenarios (Figure 2).

Within the current study the GEM-E3 model has been modified so as to incorporate learning-by-doing mechanisms and semi-endogenous energy efficiency improvements. In the following section the specification of the main part of GEM-E3 is provided (for a full specification of the model see Capros et al. 1999) and the mechanics of the newly incorporated mechanisms are detailed.

Figure 2: GEM-E3 simulation procedure



Source: E3M-Lab.

1.1 Firms

The production function of firms involves 16 intermediate inputs and two primary production factors (capital and labor). The aggregate production function used in the model is the neoclassical constant elasticity of substitution (CES, see Arrow et al. 1961). In order to capture the different substitution possibilities among the production factors, the nesting scheme of the CES presented in Figure 3 was adopted.

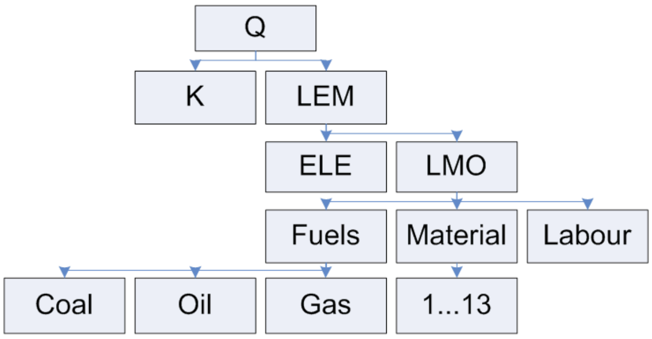
Firms seek to maximize their profits by employing the optimum amounts of intermediate and primary production factors. The firms' optimization problem is given by (1) and (2).

$$\max \Pi_i = P_i \cdot Q_i - PK_i \cdot K_i - PLEM_i \cdot LEM_i \tag{1}$$

$$\text{where } Q_i = \left(e^{tgk} \cdot d_i^k \cdot K^\rho + d_i^{lem} \cdot LEM_i^\rho \right)^{\frac{1}{\rho}} \tag{2}$$

and i is the number of firms $i = \{1 \text{ to } 25\}$, Π is profit, P_i is the unit cost of production, Q_i the volume of production; $PLEM_i$ is the unit cost of production of the bundle of labor, energy, and materials, and LEM_i the volume of this bundle; PK_i is the user cost of capital, K_i the volume of capital employed; ρ is the parameter that relates to the elasticity of substitution s as follows $s = \frac{1}{1+\rho}$ (the elasticity of substitution is indexed to i but for presentation reasons

Figure 3: GEM-E3 production nesting scheme



`Q` is production, `K` is capital, `LEM` is the energy material labor bundle, `ELE` is electricity, and `LMO` the fuel material labor bundle; Source: E3M-Lab.

this is skipped here); d_i^k and d_i^{lem} are the calibrated share parameters for capital and the LEM_i bundle respectively; and tgk is the technical progress of capital. From the first order conditions, the optimum demands for K, LEM production factors are derived (similarly for all other nestings the optimum factor demands can be derived)

$$\frac{d\Pi}{dK} = 0, \quad K_i = Q_i \cdot \left(e^{tgk} \cdot d_i^k\right)^s \cdot \left(\frac{PK_i}{P_i}\right)^{-s} \tag{3}$$

$$\frac{d\Pi}{dLEM} = 0, \quad L_i = Q_i \cdot \left(d_i^{lem}\right)^s \cdot \left(\frac{PLEM_i}{P_i}\right)^{-s} \tag{4}$$

Substituting the derived demands into the production function, the function of the unit cost of production can be derived. This is the supply function of the firm and serves as the zero profit[5] condition for the model.

$$P_i = \left[e^{-tgk \cdot s} \cdot \left(d_i^k\right)^s \cdot (PK_i)^{1-s} + \left(d_i^{lem}\right)^s \cdot (PLEM_i)^{1-s}\right]^{\frac{1}{1-s}} \tag{5}$$

Similar derivations apply for all levels of the CES nesting scheme. The respective productivities found in each level are: energy productivity (tge), materials productivity (tgm) and labor productivity (tgl).

1.2 Learning-by-doing

The learning-by-doing or experience curve has been studied extensively. It represents technical progress as a function of some cumulative experience indicator. Dasgupta and Stiglitz

---

[5] By applying the Euler equation (due to the homogeneity of 1^{st} degree in quantities of the CES) we get $\Pi \equiv \mathrm{K} \cdot \frac{d\Pi}{dK} + LEM \cdot \frac{d\Pi}{dLEM}$, that is, if each production factor is paid its marginal product then profits are zero, that is, all revenues are used for the compensation of the production factors.

(1988) assume that the size of the productivity increase through learning-by-doing is a positive function of the capital intensity of production. One should note that this type of productivity growth is not embodied in machinery and equipment, but it is not strictly disembodied either, since it needs the machinery and equipment as the object of learning. According to Lieberman (1987), a typical empirical study of the learning function, learning is found to be a function of cumulative investment rather than calendar time. Similarly Christensen (1997) uses the cumulative capacity as a measure of the knowledge accumulation occurring during the manufacturing and use of a technology.

In the version of the GEM-E3 model used in this study, learning rates in power producing sectors were introduced. A rather comprehensive review of learning curves for energy technology and policy analysis can be found in Jamasb and Köhler (2007). The usual form of learning curve measures how much the costs of a given power producing technology are reduced due to its increased capacity (Equation 6):

$$c_i = a \cdot Cap_i^{lr} \tag{6}$$

where c_i is the cost per unit of production, Cap_i is capacity and lr the learning elasticity. The learning effect is then measured in terms of percentage cost reduction for each doubling of the cumulative generation capacity or of production (equation 7):

$$LRE_i = 1 - 2^{lr} \tag{7}$$

where LRE_i is the learning effect. Thus learning by doing rates are assumed to reduce overall production costs (see also McDonald and Schrattenholzer (2001), Pizer and Popp (2007)). In the GEM-E3 model, learning rates are assumed to increase labor productivity and hence reduce labor costs. Learning in GEM-E3 has been assumed to be a function of the ratio of investment to installed capacity (i.e. capital stock). The exact specification is given in Equation 8:

$$\Omega_i = \left(\frac{INVV_i}{KS_{i,t-1}} - d + 1 \right)^{period} \cdot \Omega_{i,t-1} \tag{8}$$

where Ω_i is the learning productivity rate, $INVV_i$ is investment by firm, $KS_{i,t-1}$ is the capital stock of the previous period/year and d is the capital stock depreciation. Ω then increases the exogenous labor productivity *tgl* (*tgl* is computed during the development of the reference projection) which enters in the derived demand for labor in Equation 9:

$$\frac{d\Pi}{dL} = 0, \quad L_i = LMO_i \cdot \left(e^{tgl \cdot \Omega_i} \cdot d_i^l \right)^{s3} \cdot \left(\frac{PL_i}{PLMO_i} \right)^{-s3} \tag{9}$$

where L_i is the firms demand for labor, LMO_i is the labor, material, energy bundle, PL_i is unit cost of labor, $PLMO$ is the unit cost of the LMO bundle, d is a share parameter and $s3$ the elasticity of substitution. Jamasb and Köhler (2007) provide a survey of historical learning rates in energy-related sectors, see Table 1.

Since learning-by-doing exhibits increasing returns to scale, it was not endogenised in the GEM-E3 model (a fully endogenous specification would lead to non-convergence problems).

That means that agents (in our case power producing sectors) are not aware of the learning-by-doing effect prior to their decision to select the optimal production factor mix. The cost reduction occurs once their investment decision is made. A shortcut to semi-endogenise the learning-by-doing effect would be to follow an iterative approach (not currently modeled). That is, at the first iteration firms will decide on their optimum production factor mix without knowing the learning by doing effect. Once the mix is decided the learning productivity effect can be computed (outside the 'solve' loop of the model). Then in the subsequent iteration firms will decide on the optimal factor mix knowing the potential learning-by-doing effect (as this was computed in the previous iteration).

Table 1: Historical learning rates for selected power producing technologies

Technology	Learning rate	Reporter	Period
Hydro	1.4	OECD	1979-1993
Nuclear	5.8	OECD	1975-1993
Coal	3.7	US	1960-1980
GTCC	34	OECD	1984-1994
Biomass	15	EU	1980-1999
Wind	18	EU	1980-1995
SPV	35	EU	1985-1994

Source: Adapted from Jamasb and Köhler (2007), McDonald and Schrattenholzer (2001), Kouvaritakis, Soria and Isoard (2000).

2 Bottom Up representation of the energy sector in the GEM-E3 model

CGE models have been criticized for their simplified modeling approach of the energy system. The usual CGE representation of energy production by means of aggregate production functions fails to capture crucial characteristics of the sector reducing the credibility of simulations related to energy policies and technology dynamics. The bottom up models employed instead, ignore the feedbacks from the interaction of the energy sector with the wider economy within which it operates. The development of a modeling framework that encompasses the multi market equilibrium of top down models with an engineering consistent representation of power producing technologies constitutes a long-standing challenge in applied energy policy analysis since the hybrid CGE model of (Manne 1977). Many different approaches have been employed to link bottom up and top down models and can be classified, following Boehringer and Rutherford (2005), in two main categories: (i) hard link approach, that is, integrating both bottom-up and top-down features in a consistent modeling framework. Such an integrated framework is provided by the specification of market equilibrium models as mixed complementarity problems (see Boehringer (1998) , Frei (2001), Kumbaroglou and Madlener (2001), Kumbaroglou and Madlener (2001), McFarland, Reilly and Herzog (2004), Wing (2006)). (ii) soft-link or decomposition approach where bottom-up and top-down models are run independently of each other (Boehringer and Rutherford 2005, Hudson and Jorgenson 1974). In this case results from one model are fed into the other, and vice versa. The GEM-E3 model adopts the hard link approach and identifies the following power producing technologies: i) Coal fired, ii) Gas fired, iii) Oil fired, iv) Nuclear, v) Biomass, vi) Hydro electric vii) Wind and viii) PV. The market shares and cost characterisation of power producing technologies is based on engineering databases and energy balances such as the TECHPOL database, the ENERDATA database and the PRIMES model database. The cost structure and market shares (at the EU27 level) are depicted in the Table 2.

Table 2: Base year cost structure and market shares of power producing technologies EU27

Technology	Capital	Labour	Fuel	Market
Coal fired	46	26	28	31
Oil fired	22	11	66	6
Gas fired	21	10	69	25
Nuclear	78	22	–	24
Biomass	35	13	51	3
Hydro	87	13	–	9
Wind	92	8	–	2
PV	98	2	–	0

The shares of each technology in power generation in the base year are introduced from energy balance statistics. Some of the potential technologies that may develop in the future are not used in the base year. Since the production function for power generation is calibrated to the base year, it is necessary to introduce artificially small shares even for the non existing technologies in order to allow for the possibility of their penetration in the future under market conditions.

The input-output tables represent the electricity sector as an aggregate of two activities, namely the power generation and the transmission and distribution of electricity. This is not convenient for the bottom up model, and so it is necessary to split the Input-Output column and row in different activities, some corresponding to power generation by technology and the rest corresponding to transmission and distribution of electricity. The split was performed by combining data from energy balances and company-related economic data about generation and transmission and distribution activities by country. The aggregate data were based on Eurostat, IEA and USA DOE statistics. For example, the disaggregation shows that the generation cost accounts for over half of total cost, and in most EU countries they account for over 60 %. In order to disaggregate the power sector a mapping was specified between the entries of the Input-Output table and the engineering information retrieved from the technical databases. For this purpose the following cost elements were derived from the engineering database: (i) capital cost (ii) fixed operating and maintenance cost (iii) fuel cost and (iv) other variable operating and maintenance costs, related to the energy producing technologies to be incorporated in the model. Subsequently these unit costs are associated with the corresponding cost elements of the Input-Output statistics, according to the following principles: a) annualized capital costs correspond broadly to operating surpluses, b) fuel costs correspond to the fuel input, c) fixed operating and maintenance cost correspond to non energy inputs (materials), d) variable operating and maintenance costs are associated with wages and salaries paid to employees in power generation. Since the entire GEM-E3 model is calibrated on the social accounting matrices it is reasonable to keep the macroeconomic data constant and adjust the market and cost shares of the technologies. The purpose of the calibration is to depart as little as possible from the flows suggested by the engineering information while respecting exactly the totals appearing in the original input output table. Toward this end a cross entropy method was applied. This calibration technique cannot be applied uniformly since each country has specificities that must be respected. For example there are cases where the input output data do not register a flow from agriculture to electricity (biomass fuel), or the engineering data suggest such capital allocations that lead to unrealistic investment to capital ratios by technology. Adjustments of data were made in order to cope with these difficulties.

Table 3: Base year electricity generation costs

Technology	Cost relative to Coal fired technology
Coal fired	1
Oil fired	1.6
Gas fired	1.3
Nuclear	1.2
Biomass	1.7
Hydro	2.1
Wind	1.3
PV	4.1

The production function in GEM-E3 follows a nested scheme, involving capital (K), labor (L), energy (E) and materials (M) and is based on a CES neo-classical type of production function.

At the top level of the production function there is a CES aggregation of capital and the LEEM (labor, Energy, Electricity, Material) bundle. The elasticity of substitution at this level is 0.1. At the second level there is CES aggregation of Electricity (incl. T&D) and the LEM bundle with 0.2 elasticity of substitution. At the fourth level transmission and distribution (T&D) bundle and the power generation bundle (GEN) are aggregated through a CES function. At this level the elasticity of substitution chosen is 0.1 since these activities are considered to be complementary to each other. The power generation bundle is then a C.E.S. aggregate of a set of discrete power technologies. At the fifth nesting level a higher elasticity of substitution is chosen allowing for shifts in the technology mix of power production. The CES formulation for each level is shown below:

$$El_i = \left(d_i^{ren} \cdot (\frac{REN_i}{\overline{REN_i}})^{\rho} + d_i^{nc} \cdot (\frac{NC_i}{\overline{NC_i}})^{\rho} \right)^{\frac{1}{\rho}} \tag{10}$$

$$REN_i = \left(d_i^{hyd} \cdot (\frac{HUD_i}{\overline{HYD_i}})^{\rho 1} + d_i^{wnd} \cdot (\frac{WND_i}{\overline{WND_i}})^{\rho 1} + d_i^{pv} \cdot (\frac{PV_i}{\overline{PV_i}})^{\rho 1} + d_i^{bms} \cdot (\frac{BMS_i}{\overline{BMS_i}})^{\rho 1} \right)^{\frac{1}{\rho 1}} \tag{11}$$

$$NC_i = \left(d_i^{nuc} \cdot (\frac{NUC_i}{\overline{NUC_i}})^{\rho 2} + d_i^{cov} \cdot (\frac{COV_i}{\overline{COV_i}})^{\rho 2} \right)^{\frac{1}{\rho 2}} \tag{12}$$

$$COV_i = \left(d_i^{coa} \cdot (\frac{COA_i}{\overline{COA_i}})^{\rho 3} + d_i^{oil} \cdot (\frac{OIL_i}{\overline{OIL_i}})^{\rho 2} + d_i^{gas} \cdot (\frac{GAS_i}{\overline{GAS_i}})^{\rho 3} \right)^{\frac{1}{\rho 3}} \tag{13}$$

The output of the power producing technologies is a CES aggregate of: capital labor and fuels. A parameter is introduced reflecting the capital equipment technical progress of each technology. This parameter is used to calibrate the production cost of each technology depicted in table below.

$$Q = \left(ent_con \cdot d^k \cdot (\frac{K}{\overline{K}})^{\rho 4} + d^{lf} \cdot (\frac{LF}{\overline{LF}})^{\rho 4} \right)^{\frac{1}{\rho 4}} \tag{14}$$

$$LF = \left(d^l \cdot (\frac{L}{\overline{L}})^{\rho 5} + d^{fuel} \cdot (\frac{Fuel}{\overline{Fuel}})^{\rho 5} \right)^{\frac{1}{\rho 5}} \tag{15}$$

2.1 Energy efficiency

In the standard version of the GEM-E3 model energy efficiency improvements are simulated through the exogenously specified energy productivity (*tge*). Based on the methodology developed in previous works (Capros et al. 1998; Capros et al. 1999), energy efficiency cost curves were introduced in the model. In this specification, agents are able to use part of their income in order to increase energy efficiency. To achieve this, an additional factor was introduced, namely the stock of energy saving technology. Then energy productivity (*tge*) was formulated as a positive function of the stock of energy saving technology.

$$EFIst_{i,t} = (1 - dloss_{i,t})^{period} \cdot EFIst_{i,t-1} + \left(\frac{1 - (1 - dloss_{i,t})^{period}}{dloss_{i,t}} \right) \cdot EFIfl_{i,t} \tag{16}$$

$$EFfl_{i,t} = ac_i \cdot (EFIst_{i,t})^g \tag{17}$$

where $EFIst$ is the stock of energy saving technology, $dloss$ is the decay parameter for the energy efficiency improvements, $EFfl$ is the expenditure for energy efficiency, and ac and g are calibrated parameters of the energy efficiency cost curve.

It is important to underline the three distinctive features of the stock of energy saving technology: i) it does not increase the productive capital stock of the firm. Accumulation of the energy saving technology increases only energy productivity and hence provides energy efficiency improvements. ii) Expenditure in energy saving technology is essentially additional demand for goods and services such as equipment goods, electrical goods, construction, market services, and iii) the accumulation of energy saving technology has permanent effects on energy productivity. Energy efficiency improvements are modeled so as to exhibit decreasing marginal returns (saturation effect). It should be noted that in the current setup expenditures in energy efficiency $(EFfl)$ are assumed exogenous. This approach could be further improved by including the expenditure on energy efficiency as an endogenous choice of the agents (households and firms).

2.2 Government

Government behaviour is set exogenously in the model. Government income is generated through tax collection, property income and dividends received by firms. The world version of GEM-E3 identifies the following fiscal instruments: indirect taxes, direct taxes, subsidies, social security and duty rates. These receipts are coming from product sales (i.e. from branches) and from sectors (i.e. agents).

2.3 Households and labor market

GEM-E3 identifies a representative household per region that maximizes its utility under its budget constraint. Household budget is composed of: i) income from labor supply ii) dividends received from firms iii) public transfer payments.

The utility function is a LES (Linear Expenditure System - Stone Geary Stone 1954) type extended (Extended Linear Expenditure System) according to (Lluch 1973)[6].

$$U\left(CV, LJV\right) = \left(\beta_{\mathrm{H}} \cdot \ln\left(CV - CH\right) + \beta_{L} \cdot \ln\left(LJV - CL\right)\right) \tag{18}$$

where CV is total consumption, CH is the subsistence minimum consumption, LJV is leisure, CL is the subsistence minimum leisure, β_{H} is the LES budget share parameter (households consumption pattern), β_{L} is the leisure share parameter. The total and disposable incomes of the consumer are calculated as:

$$M = PL \cdot L + W^{oth} \tag{19}$$

$$YDISP = \mathrm{M} - S \tag{20}$$

where $PL \cdot L$ is the income from labor supply, and W^{oth} the non labor income (i.e. dividends, unemployment benefits, property income), $PLJ \cdot LJV$ is the value of leisure and S are the savings. The objective function of the household is the maximization of its intertemporal utility function subject to its intertemporal budget constraint.

$$max_{CV,LJV} \int_{t=0}^{\infty} e^{-stp \cdot t} U\left(CV, LJV\right) \tag{21}$$

$$\text{s.t. } \dot{w}\left(t\right) = YDISP\left(t\right) - PCI\left(t\right) \cdot CV\left(t\right) - PCI\left(t\right) \cdot CH\left(t\right) - PLJ\left(t\right) \cdot LJV\left(t\right) - PLJ\left(t\right) \cdot CL\left(t\right)$$

where stp is the social time preference or subjective rate of discount. The solution to the above problem[7] is given by the optimal demand for consumption and leisure (22), (23).

$$CV = ch + \mu \cdot \frac{bh}{PCI} \cdot \left(YDISP + PLJ \cdot LJV - PLJ \cdot CL - PCI \cdot CH\right) \tag{22}$$

$$LJV = cl + \mu \cdot \frac{bl}{PLJ} \cdot \left(YDISP + PLJ \cdot LJV - PLJ \cdot CL - PCI \cdot CL\right) \tag{23}$$

---

[6] Lluch extended LES so as to incorporate saving decision of households

[7] The derivation follows (Lluch 1973).

where μ is an approximation to the marginal rate of consumption $\mu = \frac{stp}{r}$, r is the interest rate (Lluch 1973). Once the household has decided on its overall consumption and leisure, it has to allocate this consumption to specific goods and services (fn). These goods and services are distinguished into durable goods (DG) and non durable goods (NDG; below, $fn = \{DG, ND\}$). At this stage the GEM-E3 model adopts the approach developed by Conrad and Schroeder (1991) where the demand system of durable and non-durable goods is a function of their price, the stock of durable goods and total expenditure. The demand for durable goods is:

$$HCFV_{DG} = chcfv_{DG} + \frac{bhcfv_{DG}}{PDUR_{DG}} \cdot \left(PCI \cdot CV - \sum_{i:nd} PHCFV_i \cdot chcfv_i \right) \tag{24}$$

where $HCFV$ is consumption by purpose, $chcfv$ is the subsistence minimum, $bhcfv$ is the LES share parameter (related to the Household consumption pattern), $PHCFV$ is the price that refers to the consumption by purpose, and $PDUR$ is the user cost of the durable good:

$$PDUR_{DG} = PHCFV \cdot (r + d) + PHCFV \cdot (mincons + DISPCONS) \tag{25}$$

Consumption of durable goods is linked with the consumption of non-durable goods (LND) (e.g. fuel for the operation of transport vehicle). This consumption is calculated as:

$$LLNDC_{LND,DG} = HCFV_{DG} \cdot (mincons_{LND,DG} + DISPCONS_{LND,DG}) \tag{26}$$

where $MINCONS$ is the minimum consumption of non durable goods required for the consumption of one unit of durable goods and $DISPCONS$ is a factor of proportions adjusted according to the variation of the relative prices:

$$DISPCONS_{LND,DG} = alphdisp_{lnd,dg} \cdot \left(\frac{PCI}{PHCFV_{lnd}} \right)^{etadisp_{lnd,dg}} \tag{27}$$

where $alphdisp$ is a share parameter, and $etadisp$ is price elasticity. Consumption of non durable goods is linked to durables, and the consumption of non-durable goods is calculated as:

$$\begin{aligned} HCFV_{LND} = chcfv_{lnd} + \frac{bhcfv_{lnd}}{PHCFV_{lnd}} \cdot \left(PCI \cdot CV - \sum_{i:lnd} PHCFV_i \cdot chcfv_i \right) \\ + \sum_{dg} LLNDC_{LND,DG} \end{aligned} \tag{28}$$

$$HCFV_{ND} = chcfv_{nd} + \frac{bhcfv_{nd}}{PHCFV_{nd}} \cdot \left(PCI \cdot CV - \sum_{i:nd} PHCFV_i \cdot chcfv_i \right) \tag{29}$$

Thus the consumer decides upon the consumption of durable goods not only according to their price but also according to the cost of goods and services linked to the consumption of durable goods. The consumption by purpose is translated to demand for consumption products through the consumption matrix. GEM-E3 uses fixed factor coefficient consumption matrices. Thus the final consumption demand by households is calculated from:

$$HCV_{pr} = \sum_{fn} tchcfv_{pr,fn} \cdot HCFV_{fn} \tag{30}$$

with $tchcfv$ representing the fixed factor coefficient consumption matrices.

Unemployment in pure competitive general equilibrium models is usually voluntary and it is the result of the households decision for leisure. A way of simulating involuntary unemployment relates to the assumption that there is a negative correlation between wages and unemployment. This approach is consistent with the efficiency wages theory of Shapiro and Stiglitz (1984) which states that productivity/quality of labor has a positive correlation with wages. In periods with high unemployment, firms are not motivated to offer high wages to attract higher quality labor or to increase productivity of existing workers. On the other hand, at low unemployment rates it is efficient for firms to offer wages above their equilibrium level, because they seek for increases in labor productivity and for reducing the probability of someone quitting the job and hence reducing costs from the recruitment of new personnel (Phelps 1998; Campbell and Orszag 1998). In the GEM-E3 model the efficiency wage approach is adopted for representing involuntary (equilibrium) unemployment.

This modeling approach was preferred because of its empirical validation, by using for example Blanchflower and Oswald (1994), its simplicity, and the fact that it is parsimonious in parameters. The specification of efficiency wages in GEM-E3 is shown below and it is based on Shapiro and Stiglitz (1984) and Annabi (2003):

The utility function of a "shirker" worker U_s is defined as:

$$r \cdot U_s = w - (q + b) \cdot (U_s - U_u) \tag{31}$$

where q is an efficiency related parameter, b is a quit-job-rate, r the interest rate, w the wage and U_u the utility function of the unemployed. The utility function of a "non-shirker" is:

$$r \cdot U_n = w - e - b \cdot (U_n - U_u) \tag{32}$$

where $e \geq 0$ is the disutility from working (for the "shirker" $e = 0$). The utility function of the unemployed is:

$$r \cdot U_u = \overline{wr} + a \cdot (U_n - U_u) \tag{33}$$

where $\overline{wr}$ is the unemployment benefit and a the probability to get a job.

A worker decides not to be productive when $U_n \geq U_s$. This is the efficiency condition. Replacing the utility functions of the shirker and non-shirker, the efficiency condition can be rewritten as:

$$w \geq \overline{wr} + e + \frac{e \cdot (a + b + r)}{q} \tag{34}$$

Thus, the efficiency wage is an increasing function of the quit rate, the probability of finding a job, the interest rate, and the unemployment benefit. In equilibrium, the number of workers that are unemployed should equal the number of workers that fill a vacancy

$$b \cdot L = a \cdot (LS - L) \tag{35}$$

The unemployment rate is defined as

$$u = \frac{LS - L}{LS} \tag{36}$$

Thus the efficiency condition (unemployment wage function) becomes:

$$w = \overline{wr} + e + \frac{e}{q} \cdot \left(\frac{b}{u} + r \right) \tag{37}$$

This equation serves as the labor supply function in GEM-E3. The condition was adjusted so as to incorporate real wages. This replaces the previous labor market equilibrium condition, i.e. $LAV^s = LAV^D$ from which the equilibrium wage rate was derived. PCI is the consumer price index and eg an adjustment parameter to reflect the different labor market flexibility conditions that prevail in each country.

$$w \cdot \frac{PCI}{\overline{PCI}} = \overline{wr} + e + \frac{e}{q} \cdot \left[\left(\frac{b}{u} \right)^{eg} + r \right] \tag{38}$$

2.4 Environment

The GEM-E3 model incorporates all GHG emissions and their associated marginal abatement cost curves. There are three mechanisms that affect the level of actual emissions in the GEM-E3 model:

- End-of-pipe abatement (process related GHG emissions and pollutants SO_2, NO_x, VOC, PM): end-of-pipe abatement technologies are formulated explicitly by bottom-up derived abatement cost functions. These cost functions differ between sectors, GHGs and countries.

- Substitution of fuels (all fuels): as the production of the sectors is specified in nested CES-functions, there is (at least for a substitution elasticity greater than 0) some flexibility in the decision of intermediate consumptions. Input demand is linked to the relative prices of these inputs. Hence, if there is an extra cost on energy inputs, there will be a shift in the intermediate demand away from ‘expensive’ energy inputs towards less costly inputs. Any cost of emissions therefore drives substitution towards less emission intensive inputs, e.g. from coal to gas or from energy to materials, labor or capital.

- Decline in production: in a general equilibrium system that reflects the interdependency of agents' decisions, imposing an environmental constraint (through standards, taxes or other policy instruments) entails additional costs of production (which is linked to the costs of substitution or abatement installations). The resulting increased output price implies a decrease in demand of these goods even if this demand is relatively inelastic to price changes, because of budget constraints. This further implies a lowering in production and accordingly lower demand for intermediate consumption. Hence, there is an emission reduction due to a demand driven decline in production.

The abatement activities are modeled so as to increase the user cost of the polluting input (for example the price of energy or the unit cost of production for process related GHG emissions) which influences the decision process of the firm. The price of energy, including of abatement cost and taxes, is used in the decision of the firm about the choice of production factors (at the energy level and implicitly at the level of aggregates); it represents the user's cost of energy. Upwards sloping marginal abatement cost curves are incorporated for all non-energy related GHG emissions. When an environmental tax is imposed, the firm causing the pollution pays to the government.

In the modeling of the abatement activities, installing abatement technologies (i.e. the demand for goods and services that implement the technology) entails additional costs which have been considered as corresponding to inputs to production and not as an investment. The major advantage of this formulation is its simplicity, especially as the available abatement cost functions are in terms of annualized costs, and because, with this framework, the abatement costs do not directly increase GDP as it would be the case if modeled as investment in which case a depreciation and replacement mechanism would have to be introduced. The user's cost of the abatement equipment would have to be added to the capital income, avoiding however any double counting. The input demand for abatement is modeled in the following way:

- the demand for abatement inputs is allocated to the delivery sectors through fixed coefficients;
- the total delivery for abatement is added to the intermediate demand and these inputs are valued as the other intermediate deliveries.

The total abatement cost for the firm is:

$$TCA_i = AA_i \cdot AC_i\left(AA\right) \cdot Ef_i \cdot Q_i \tag{39}$$

where AA is the degree of abatement, AC the average cost of abatement, Ef the emission factor and Q_i level of production of activity i.

The average cost is:

$$AC_i\left(AA\right) = \frac{TCA_i}{AA_i \cdot Ef_i \cdot Q_i} \tag{40}$$

The firm minimizes its cost subject to its production function (w is the real wage, L is labor, r is the user cost of capital and K capital flow):

$$\min TC_i = w_i \cdot L_i + r_i \cdot K_i + (1 - AA_i) \cdot Ef_i \cdot T_i \cdot Q_i + AC_i\,(AA) \cdot AA_i \cdot Ef_i \cdot Q_i \quad (41)$$

$$\text{s.t. } Q_i = \left(e^{tgk} \cdot d_i^k \cdot K^\rho + d_i^{lem} \cdot LEM_i^\rho\right)^{\frac{1}{\rho}}$$

From which the marginal cost is derived as:

$$T_i = \frac{MC_i}{Ef_i \cdot Q_i} \quad (42)$$

$$MC_i = mc_i(AA) \cdot Ef_i \cdot Q_i \quad (43)$$

Thus the optimal degree of abatement is derived from equating marginal cost with taxed emissions. The marginal cost function for abatement in GEM-E3 is $mc_i = c_i \cdot \left(e^{AA} - 1\right)$ and the total cost (integral of the marginal cost) is $CABAVV_i = c_i \cdot \left(AA_i - e^{AA}\right)$. The coefficient c was estimated for each greenhouse gas, activity and sector available in (United States Environmental Protection Agency 2005). Table 4 presents the estimations of the world Marginal Abatement Cost Curves (MACCs) of GEM-E3 based on the EPA data.

Table 4: Estimation of GEM-E3 World MACC

Activities	GHG	Estimation (C1)
Agriculture	CH_4	230.14
Agriculture	N_2O	97.20
Solvents	HFC	152.71
Semiconductors	PFC	26.00
Refrigeration	HFC	349.00
Oil	CH_4	180.79
Gas	CH_4	150.16
Nitric Acid	N_2O	26.13
Magnesium	SF_6	16.06
Landfills	CH_4	127.75
HCFC	HFC	22.86
Foams	HFC	115.09
Electric T&D	SF6	26.62
Coal	CH_4	89.87
Aluminum	PFC	114.37
Adipic Acid	N_2O	15.48

Source: E3M-Lab estimations.

The EPA report provided data for the following countries/regions: Africa, Annex I, Australia and New Zealand, Brazil, Canada, China, CIS, Eastern Europe, EU15, India, Japan, Latin America/Caribbean, Mexico, Middle East, Non-EU Europe, Non-OECD Annex I, OECD, OPEC, Russian Federation, South & SE Asia, South Korea, Turkey, Ukraine, United States, World. Marginal abatement costs were available for the years 2010 and 2020.

Each GHG emitting activity is linked to the GEM-E3 production sectors according to Table 5.

To simulate GHG mitigation policies the user of the model has two options either to impose an energy/environmental tax or to impose an emission reduction constraint. A binding emission reduction constraint generates a dual value which in equilibrium will be equal to the marginal cost of abatement. Permits can be auctioned or freely allocated (based for example on grand-fathering). Public revenues from auctioned permits can be recycled into the economy through the following channels: i) reducing employers' social security contributions, ii) support households' income through lump-sum transfers iii) finance carbon free technologies. The firms' revenues from permit sales can be redirected to firms' capital income or to reduce overall production costs.

Table 5: GEM-E3 activities linked to non-energy related GHG emissions

No	Activity	GHG
1	Agriculture	CH_4, N_2O
2	Coal	CH_4
4	Natural Gas	CH_4
5	Electricity	SF_6
6	Ferrous and non ferrous metals	PFCs, SF_6
7	Chemical industry	HFCs
8	Rest of energy intensive industries	CO_2
9	Electrical goods	HFCs
10	Equipment manufacturing	PFCs, SF_6
11	Transport	N_2O
12	Waste disposal (Non market services)	CH_4

Source: E3M-Lab.

3 Investment

The basic methodology approaches for modeling investment behaviour relate to the accelerator model AM[8] and to Tobin's Q (Tobin 1969) [9]. GEM-E3 is based on these two approaches. It starts from Ando et al. (1974) according to which investment is defined as $I_t = \hat{k}_t \cdot \Delta X_t^c$ where $\hat{k}_t$ is the capital to output ratio and ΔX_t^c is the net change in firms productive capacity. In GEM-E3 the optimum derived demand for capital K^* is a function of the capital to output ratio and of the relative prices. The capital stock update is provided by the following motion equation:

$$KAVC_t = (1-d)^t \cdot KAVC_{t-1} + INVV_t \tag{44}$$

Thus investment is equal to the change in the productive capacity of the firm plus capital depreciation:

$$INVV_t = \Delta X_t + d \cdot KAVC_{t-1} \tag{45}$$

---

[8] The AM model assumes that the optimal demand for capital is a function of output $K_t^* = \mu_t \cdot Q_t$. Prices, wages and interest rates do not affect capital demand. The AM assumes instantaneous capital adjustment to its optimal level hence $I_t = K_t^* - K_{t-1}^* = \mu \cdot (XD_t - XD_{t-1})$. A variation of this approach relates to the non-instantaneous adjustment of capital: $I_t = \lambda \cdot (K_t^* - K_{t-1}^*)$.

[9] According to which net investment depends on the market price of capital and on its replacement cost.

Change in productive capacity ΔX_t is derived from the comparison of previous year capital stock $KAVC_{t-1}$ with the optimum demand of current year K_t^*. Using the average Tobin Q (Hayashi 1982), firms take into account both the cost of capital and its replacement cost $\frac{PK}{PINV \cdot (r+d)}$, which leads to:

$$INVV_t = K_t^{\cdot} \cdot \left(\frac{PK}{PINV \cdot (r+d)} - 1 + d \right) \tag{46}$$

Since GEM-E3 is not a fully dynamic model, firms' expectations for next period growth $stgr$ are defined exogenously, hence the investment function of the model becomes:

$$INVV_t = K_t \cdot \alpha 0 \cdot \left[\left(\frac{PK}{PINV \cdot (r+d)} \right)^{s1 \cdot \alpha 1} \cdot (1 + stgr) - (1 - d) \right] \tag{47}$$

where $\alpha 0$ and $\alpha 1$ reflect the adjustment cost of capital and the price elasticity, respectively. (α^0 is analogous to λ of the accelerator model where capital does not adjust instantly). The unit cost of capital is derived as a dual from the equilibrium equation (supply of capital should be greater or equal to demand):

$$KAVC_t \geq K_t^* \tag{48}$$

Investment expenditures from firms are translated to demand for specific investment goods through a fixed factor coefficient investment matrix $tinvpv_{pr,br}$:

$$INV = \sum_{pr} \sum_{br} tinvpv_{pr,br} \cdot INVV_{br} \tag{49}$$

3.1 Trade

Final and intermediate consumers use a composite good (Y) that consists of domestically produced goods (XXD) and imports (IMP), following Armington (1969).

The buyer of the composite good seeks to minimize its total cost by choosing the optimum mix of XXD and IMP based on their relative prices and substitutability. The total expenditure on the composite good equals the expenditure in buying domestically produced goods and imported:

$$PY_i \cdot Y_i = PXD_i \cdot XXD_i + PIMP_i \cdot IMP_i \tag{50}$$

Imports and domestically produced goods are aggregated through a CET (constant elasticity of transformation) function:

$$Y_i = \left[\left(d_i^{xxd} \right)^{\frac{1}{sx}} \cdot (XXD_i)^{\frac{sx-1}{sx}} + \left(d_i^{imp} \right)^{\frac{1}{sx}} \cdot (IMP)^{\frac{sx-1}{sx}} \right]^{\frac{sx}{sx-1}} \tag{51}$$

where d_i^{xxd}, d_i^{imp} are the CET share parameters calibrated in the base year values, sx is the Armington elasticity of substitution and AC is the proportionality factor. The optimum demands for imports and domestically produced goods are:

$$XXD_i = Y_i \cdot AC_i^{sx-1} \cdot d_i^{xxd} \left[\frac{PY_i}{PXD_i}\right]^{\frac{1}{1-s}} \tag{52}$$

$$IMP_i = Y_i \cdot AC_i^{sx-1} \cdot d_i^{imp} \left[\frac{PY_i}{PIMP_i}\right]^{\frac{1}{1-s}} \tag{53}$$

In the next stage consumers decide on their optimum import demand by country:

$$IMPO_{i,j} = b_{i,j} \cdot IMP \cdot \left(\frac{PIMP_i}{PWXO_i}\right)^{si} \tag{54}$$

where $PWXO$ is the export price.

4 Elasticities

Two groups of parameters are distinguished in CGE models. The first group contains the parameters that are "initialised" via calibration as this is defined by Mansur and Whalley (1984) and the second group contains the parameters whose values are extracted from the relevant literature. The elasticity of substitution for each of the CES nesting levels, the income elasticities and the Armington elasticities used in the GEM-E3 model are presented in the following tables.

Table 6: Income elasticities

	σ_{fn}
Food beverages and tobacco	0.78
Clothing and footwear	0.6
Housing and water charges	1
Fuels and power	0.9
Household equipment and operation excl. heating and cooking appliances	0.4
Heating and cooking appliances	0.7
Medical care and health	0.74
Purchase of vehicles	0.4
Operation of personal transport equipment	1.2
Transport services	1.1
Communication	1.1
Recreational services	1.35
Miscellaneous goods and services	1.35

Source: E3M-Lab.

Table 7: Substitution elasticities

	$\sigma_{k,lem}$	$\sigma_{ele,lmo}$	$\sigma_{lav,ma,en}$	σ_{ma}	σ_{en}
Agriculture	0.3	0.2	0.5	0.2	0.6
Coal	0.15	0.1	0.1	0.1	0.1
Oil	0.15	0.1	0.1	0.1	0.1
Gas	0.15	0.1	0.1	0.1	0.1
Electricity	0.3	0.2	0.5	0.6	0.9
Ferrous and non ferrous Metals	0.4	0.2	0.5	0.5	0.9
Chemical industry	0.4	0.2	0.5	0.5	0.9
Rest of energy intensive industry	0.4	0.2	0.5	0.5	0.9
Electrical goods	0.4	0.2	0.5	0.3	0.6
Transport equipment	0.4	0.2	0.5	0.3	0.6
Rest of equipment manufacturing	0.4	0.2	0.5	0.3	0.6
Consumer goods industries	0.4	0.2	0.5	0.3	0.6
Construction	0.4	0.2	0.5	0.3	0.6
Telecommunication	0.4	0.2	0.5	0.3	0.6
Transport	0.4	0.2	0.5	0.3	0.6
Financial services	0.3	0.2	0.5	0.3	0.6
Market services	0.3	0.2	0.5	0.3	0.6
Non-market services	0.3	0.2	0.5	0.3	0.6

Source: E3M-Lab.

Table 8: Armington cities

	$\sigma_{d.m}$	σ_{m}
Agriculture	1.2	1.6
Coal	0.3	0.1
Oil	0.1	0.1
Gas	0.1	0.1
Electricity	0.3	0.3
Ferrous and non ferrous Metals	1.5	2.4
Chemical industry	1.5	2.4
Rest of energy intensive industry	1.5	2.4
Electrical goods	1.5	2.4
Transport equipment	1.5	2.4
Rest of equipment manufacturing	1.5	2.4
Consumer goods industries	1.7	2.8
Construction	0.6	1.6
Telecommunication	0.6	1.6
Transport	0.8	2.4
Financial services	0.6	1.6
Market services	0.6	1.6

Source: E3M-Lab.

References

Ando, A., Modigliani, F., Rasche, R. and Turnofsky, S. (1974): *On the role of expectations of price and technological change in investment function*. International Economic Review, 15, No. 2, 384–414

Annabi, N. (2003): *Modeling labour Market in CGE Models*. PEP Working Paper

Armington, P.S. (1969): *A Theory of Demand for Products Distinguished by Place of Production*. IMF Staff Papers, 16, No. 1, 159–176

Arrow, K.J., Chenery, H.B., Minhas, B.S. and Solow, R.M. (1961): *Capital-labor substitution and economic efficiency*. Review of Economics and Statistics, 43, 225–250

Babiker, M., Gurgel, A., Paltsev, S. and Reilly, J. (2009): *Forward-looking versus Recursive-dynamic Modeling in Climate Policy Analysis: A Comparison*. Economic Modelling, 26, No. 6, 1341–1354

Blanchflower, D.G. and Oswald, A.J. (1994): *The wage curve*. MIT Press

Boehringer, C. (1998): *The Synthesis of Bottom-Up and Top-Down in Energy Policy Modeling*. Energy Economics, 20, No. 3, 233–248

Boehringer, C. and Rutherford, T.F. (2005): *Combining Top-Down and Bottom-Up in Energy policy analysis: A decomposition approach*. : Discussion Paper ZEW

Brown, J., Johnson, F. A., Mehran, F., Lepper, F. and Vittorelli, C. (2009): *Economically active population: Estimates and projections' 5^{th} edition*. ⟨URL: http://laborsta.ilo.org/applv8/data/EAPEP/eapep_E.html⟩ – visited on 14.11.2010

Campbell, C. and Orszag, J.M. (1998): *A model of the wage curve*. Economics Letters, 59, No. 1, 119–125

Capros, P., Georgakopoulos, T., Filippoupolitis, A. and Kotsomiti, S. (1998): *Energy saving investment and employment: Analysis through the GEM-E3 model, the case of Greece*. : funded by the European Commission SAVE programme, contract XVII/4.1031/D/97-032 ⟨URL: http://www.e3mlab.ntua.gr/reports/ecn3.pdf⟩ – visited on 15.11.2010

Capros, P., Georgakopoulos, T., Filippoupolitis, A., Kotsomiti, S., Proost, G. Atsavesand S., Van Regemorter, D., Conrad, K. and Schmidt, T. (1999): *The GEM-E3 model: reference manual*. ⟨URL: http://www.e3mlab.ntua.gr⟩ – visited on 15.11.2010

Christensen, C.M. (1997): *Making strategy: Learning by doing*. Harvard Business Review

Conrad, K. and Schroeder, M. (1991): *Demand for durable and nondurable goods, environmental policy and consumer welfare*. Journal of Applied Econometrics, 6, 271–286

Conte, A., Labat, A., Varga, J. and Zarnic, Z. (2010): *What is the growth potential of green innovation? An assessment of EU climate policy options*. Directorate General Economic and Monetary Affairs, European Commission (413). – European Economy - Economic Papers

Dasgupta, P. and Stiglitz, J.E. (1988): *Learning-by-Doing, Market Structure and Industrial and Trade Policies*. Oxford Economic Papers, 40, No. 2, 246–68

Decaluwe, B. and Martens, A. (1988): *CGE modeling and developing economies: A concise empirical survey of 73 applications to 26 countries*. Journal of Policy Modeling, 10, No. 4, 529–568

Decaluwe, B., Martens, A. and Monette, M. (1987): *Macroclosures in Open Economy CGE Models: a Numerical Reappraisal*. Universite de Montreal, Departement de sciences economiques – Cahiers de recherche

European Commission (DG ECFIN) and the Economic Policy Committee (AWG) (2009): *The 2009 Ageing Report : Economic and budgetary projections for the EU-27 Member States (2008-2060)*. ⟨URL: http://ec.europa.eu/economy_finance/publications/publication_summary14911_en.htm⟩ – visited on 14.11.2010

Frei, C. W. (2001): *Bottom-up activity analysis in a computable general equilibrium framework*. Ph. D thesis, Lausanne, ⟨URL: http://library.epfl.ch/theses/?nr=2327⟩

Hayashi, F. (1982): *Tobin's Marginal q and Average q: A Neoclassical Interpretation*. Econometrica, 50, No. 1, 213–224

Hudson, E. A. and Jorgenson, D.W. (1974): *US energy policy and economic growth, 1975–2000*. The Bell Journal of Economics and Management Science, 5, No. 2, 461–514

Jamasb, T. and Köhler, J. (2007): *Learning curves for energy technology and policy analysis: A critical assesment*. Faculty of Economics, University of Cambridge – Cambridge Working Papers in Economics

Jorgenson, D.W., Slesnick, D. and Wilcoxen, P.J. (1992): *Carbon Taxes and Economic Welfare*. Harvard Institute of Economic Research (1589). – Working Papers

Kouvaritakis, N., Soria, A. and Isoard, S. (2000): *Modelling energy technology dynamics: methodology for adaptive expectations models with learning by doing and learning by searching*. International Journal of Global Energy Issues, 14, 1–4

Kumbaroglou, G. and Madlener, R. (2001): *A description of the hybrid bottom up cge model screen with an application to Swiss climate policy analysis*. : CEPE working paper no 10

Lieberman, M.B. (1987): *The Learning Curve, Diffusion, and Competitive Strategy*. Strategic Management Journal 8, No. 5

Lluch, C. (1973): *The Extended Linear Expenditure System*. European Economic Review, 4, 21–31

Löfgren, H., Harris, R. L. and Robinson, S. (2001): *A standard computable general equilibrium (CGE) model in GAMS*. International Food Policy Research Institute (IFPRI) (75). – TMD discussion papers

Manne, A. (1977): *ETA-MACRO: A Model of Energy-Economy Interactions*. In **Hitch, C. J., editor:** Modeling - Energy-Economy Interaction, Resources for the Future.

Manne, A.S. and Richels, R.G. (1997): *On stabilizing CO_2 concentrations - cost-effective emission reduction strategies*. Environmental Modeling and Assessment, 2, 251–265

Mansur, A. and Whalley, J. (1984): *Computable general equilibrium modelling for policy analysis and forecasting*. In **Scarf., H. and Shoven, J. B, editors:** Applied General Equilibrium Analysis. Cambridge University Press, 69–126

McDonald, A. and Schrattenholzer, L. (2001): *Learning rates for energy technologies*. Energy Policy, 29, 255–261

McFarland, J. R., Reilly, J. and Herzog, H. J. (2004): *Representing Energy Technologies in Top-down Economic Models Using Bottom-up Information*. Energy Economics, 26, No. 4, 685–707

McKibbin, W.J. and Wilcoxen, P.J. (1995): *The Theoretical and Empirical Structure of the G-Cubed Model*. Brookings Institution – Working Papers

Nordhaus, W. (2005): *Life After Kyoto: Alternative Approaches to Global Warming*. National Bureau of Economic Research, Inc – NBER Working Papers

Phelps, E. (1998): *Structural slumps: the modern equilibrium theory of unemployment, interest, and assets*. Harvard University Press

Pizer, W.A. and Popp, D. (2007): *Endogenizing Technological Change: Matching Empirical Evidence to Modeling Needs.* Washington: RFF Discussion Paper 07-11, Resources for the Future

Proost, S. and Van Regemorter, D. (1992): *Economic effects of a carbon tax : With a general equilibrium illustration for Belgium*. Energy Economics, 14, No. 2, 136–149

Shapiro, C. and Stiglitz, J. (1984): *Equilibrium unemployment as a worker discipline device*. American Economic Review, 74, No. 3, 155–173

Stone, R. (1954): *Linear expenditure systems and demand analysis: An application to the pattern of British demand*. Economic Journal, 255, 511–527

Tobin, J. (1969): *A general equilibrium approach to monetary theory*. Journal of Money, Credit and Banking, 1, No. 1, 15–29

United States Environmental Protection Agency (2005): *Global mitigation of non* CO_2 *greenhouse gasses.*

Wing, I. S. (2006): *The synthesis of bottom-up and top-down approaches to climate policy modeling: Electric power technologies and the cost of limiting US CO2 emissions.* Energy Policy, 34, No. 18, 3847 – 3869