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The Dynamics of Innovation and Investment and its Impact on Policy Design in Energy and Environment for a Sustainable Growth in Europe.

PROPOSAL N°: NNE5-2001-00775 (DYN-GEM-E3)

Final Report.

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1. Introduction.

Learning curve relationships are a well-established vehicle through which technical progress is endogenised in models. In particular the one factor learning or experience curve (learning-by-doing) has been studied extensively. It represents technical progress as a function of some cumulative experience indicator. Lieberman (1984) is a typical empirical study of the learning function. Empirical results exhibit a strong and consistent learning effect. Learning is found to be a function of cumulative investment rather than calendar time. However in recent years a lot of attention has been paid on extensions to the dynamics of technological progress. Thus in order to capture both the effects induced by learning-by-doing and learning-by-searching (R&D) the traditional learning curve concept is extended by a second factor usually represented by cumulative energy R&D expenditures.

The original formulation of the two-factor learning curve as proposed by Kouvaritakis *et a*l.(2000) has both cumulative capacity and cumulative R&D as two independent variables explaining cost reductions. The cumulative capacity is used as a measure of the knowledge accumulation occurring during the manufacturing and use of one technology (Christiansson, 1995) and the cumulative research and development expenditure is a measure for the learning by searching progress.

The introduction of two-factor learning curve relationships strengthens the credibility of CGE analysis in view of a more complete and real representation of technological dynamics and at the same time enables the analysis of R&D intervention, which opens the way for investigating the economic impact of alternative R&D policies favoring specific power generating technologies.

In order to implicitly incorporate two factor learning curves relationships in the GEM-E3 model its bottom up top down specification had to be revised. Revision took place upon five main axes (i) new features related to the investment behaviour of electricity technologies were installed (ii) a new bottom up database covering all EU member states was developed (iii) the number of electricity technologies was increased, (iv) a link between electricity technologies investment and power equipment industry was created and (v) a new modeling approach related to electricity production function was adopted in order to smooth out shifts in the technology mix of energy production.

2. The Bottom Up Top Down version of GEM-E3 model.

2.1. Bottom Up Top Down (BUTD) modeling approaches.

CGE models have been criticised for their simplified modelling approach of the energy system. The usual CGE representation of energy production by means of aggregate production functions fail 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 modelling 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 Alan Manne (1977)[1]. Many different approaches[2] have been employed to link bottom up and top down models and can be classified in two main categories:

(i) Hard link approach, that is, integrating both bottom-up and top-down features in a consistent modelling framework. Such an integrated framework is provided by the specification of market equilibrium models as mixed complementarity problems (see Cottle and Pang [1992], Rutherford [1995]).

(ii) Soft-link or decomposition approach where bottom-up and top-down models are run independently of each other (Boehringer & Rutherford (2006), Bergmann [1990], Hudson and Jorgenson [1974]). In this case results from one model are fed into the other, and vice versa.

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[1] ETA – Macro model where the process analysis ETA sub model of the U.S. energy system was linked with a one sector macro-model of the U.S. economy in a non linear optimization framework

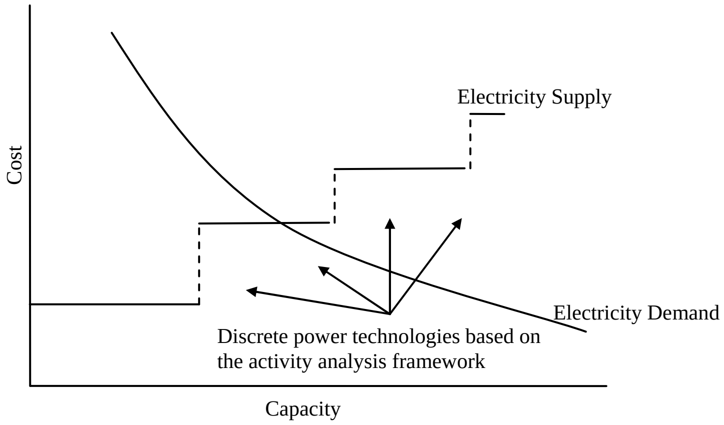
[2] Jochem 1999, Muller 2000, Kemfert [1]). Messner and Schratenholzer, Koopmans and Willem te Velde 2001, Arikan and Kumbaroglou 2001.

A characteristic example of the first category is Boehringer (1998) where electricity generating technologies are modelled as specific activities within a mathematical-programming representation of the electricity sector, which is embedded directly in a computable general equilibrium model. In particular his approach is based on the complementarity formulation of the general equilibrium problem while the representation of the electricity producing sectors is based on Koopmans (1951) activity analysis framework. The standard aggregate production functions (C.E.S. or CD) used in the model are replaced by a set of discrete Leontief technologies (fixed input/output vector).

Towards the same direction lies [McFarland et al. (2002), EPPA model] who suggest a more flexible format through a C.E.S. representation of energy technologies. Their approach consists of splitting the energy sector using engineering bottom up data and then calibrate the models' smooth production functions on these data. In particular in their approach the cost estimates on capital, labour, and fuel inputs are used directly as the CES share parameters. The nesting scheme of the production function allows for the appropriate input substitution while the control of technology penetration rate is based on an endogenous quasi fixed factor coefficient introduced at the top level of the C.E.S. production function. Each technology produces electricity through a C.E.S. aggregation of its primary and secondary inputs (low elasticities of substitution chosen at this nesting level), while total electricity production results from a CES aggregation of all power technologies represented in the model (high elasticities of substitution at this nesting level).

The shortfall of this approach lies in its treatment of investment decisions. That is, investment is either allocated to electricity technologies exogenously or decided at the level of the aggregate electricity sector and then allocated to each technology using a logit function. This investment formulation although it allows for multiple technologies with different costs to coexist is not sufficient to represent the investment behavior of the electricity sector (i.e. each sector should decide the level of investment as a function of its profit function and then this investment demand should be translated to demand for investment products produced by other sectors). In addition the non-smooth (kinked) representation of power supply results in sharp shifts in the technology mix of electricity production (Figure 1) implying unrealistic switching between technologies.

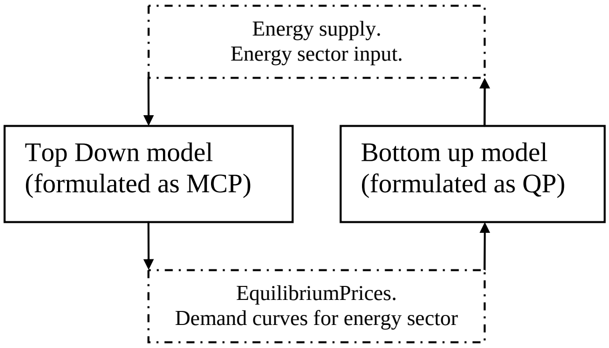
Figure 1: "Knife edge" switching between technologies.



The second category refers mainly to a decomposition method that links bottom up models with top down by combining different mathematical formats – mixed complementarity and mathematical programming. In Boehringer & Rutherford (2006) mixed complementarity methods (MCP) are used to solve the top-down economic equilibrium model and quadratic programming (QP) to solve the underlying bottom-up energy supply model. Then they reconcile equilibrium prices and quantities between both models through an iterative procedure (Figure 2 portray this iterative solution process).

Hybrid **B**ottom **U**p **T**op **D**own (**BUTD)** CGE models are still rare in the policy modelling literature due to difficulties arising from the integration of macroeconomic and engineering data in a consistent way. Within the DYN-GEM project E3 -MLab designed and incorporated into the GEM-E3 model a new bottom up top down module. The motivation for this development was the need for a better representation of the electricity sector investment decision. Toward this end electricity producing technologies were treated as separate production sectors whilst their investment decision follows Ando Modigliani [1974]. The advantage of this approach is that it is fully consistent with the general equilibrium framework while it leads to a full identification of the technologies. The rest of this section provides details on the exact formulation of the newly incorporated electricity producing sectors and on the reconciliation of engineering and input output economic data.

Figure 2: Iterative decomposition algorithm suggested by Boehringer & Rutherford (2006).



2.2. The engineering bottom up data.

The building block of CGE models is the social accounting matrices that represent flows of all economic transactions that take place within an economy (regional on national). Although these matrices can be very detailed[3] the energy producing sector is always aggregated and there is no information on discrete power producing technologies. Such information can be extracted from technical engineering databases and energy balances. For the present study the *TECHPOL* database, the ENERDATA database and the POLES[4] model database were exploited in order to extract the appropriate data. The technologies selected for the BUTD module of the GEM-E3 model are presented in Table 1.

Table 1: Electricity Producing Technologies represented in GEM-E3 model.

No	Name	Description
1	COA	Coal conventional thermal
2	CCO	Clean Coal
3	ICO	Integrated coal gasification
4	GS1	Gas conventional thermal
5	GS2	Gas turbine combined cycle
6	OL1	Oil conventional thermal
7	NK1	Nuclear (2nd - 3rd)
8	NK2	Nuclear (4th)
9	BGT	Biomass gasification plus combined cycle
10	HD1	Hydro electric
11	WID	Wind
12	SPP	Solar thermal power plant cylindro-parabolic
13	DPV	Building integrated photovoltaic

The bottom up engineering information required for the introduction of these technologies in the GEM-E3 model relates to:

(i) generation costs

(ii) technology market shares

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[3] The input output tables published freely by Eurostat refer to a 59 sectoral aggregation.

[4] Results from “Cascade Mints Contract No SSP6-CT-2003-502445”

(iii) cost share of transmission and distribution to total cost of electricity production.

2.2.1. Generation costs and market shares.

Electricity producing technologies are characterised by differing cost structures and conversion efficiencies. The estimates on capital, labour and fuel costs are substantial since these will determine how changes in various factor prices will affect each technology. Generation costs can be grouped in three main categories (i) Investment costs (ii) Operating and maintenance costs and (iii) fuel costs. Cost estimates for these categories were extracted from the *TECHPOL* database. The technologies incorporated in the model are classified at two main groups:

Those existing in the base year and their market penetration is assumed to be mature:

1. Coal conventional thermal.
2. Gas conventional thermal
3. Oil conventional thermal
4. Nuclear (2nd and 3rd generation)
5. Hydro electric.

and at those with incomplete penetration rates:

1. Clean coal
2. Integrated coal gasification
3. Gas turbine combined cycle
4. Nuclear 4th generation
5. Wind
6. Solar thermal power plant cylindro parabolic
7. Builing integrated photovolotaic.

The specific cost structure of each technology introduced in the model is presented in Table 2.

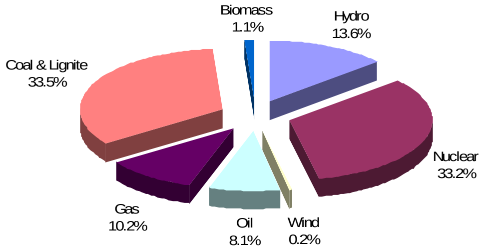
Table 2: Electricity production cost shares.

	Coal conventional thermal (COA)	Clean Coal (CCO)	Integrated Coal gasification (ICO)	Gas conventional thermal (GS1)	Gas turbine combined cycle (GS2)	Oil conventional thermal (OL1)	Nuclear (2n -3rd) (NK1)	Nuclear (4th) (NK2)	Biomass (BGT)	Hydro electric (HD1)	Wind (WID)	Solar thermal (SPP)	Photovoltaics (DPV)
Capital	0.46	0.51	0.53	0.21	0.15	0.22	0.78	0.86	0.35	0.87	0.84	0.92	0.95
Labour	0.26	0.25	0.28	0.10	0.11	0.11	0.22	0.14	0.13	0.13	0.16	0.08	0.05
Coal	0.27	0.24	0.19										
Oil						0.66							
Gas				0.69	0.73								
Agriculture									0.51				

Source: Calculations based on TECHPOL database.

Base year technology market shares have a special meaning in the general equilibrium approach since it is assumed that the power sector in this year is in equilibrium: that is, market shares provide the model with the equilibrium point from which the energy technologies will start to compete. Thus in order to model non existing (at the base year) technologies one should add them explicitly at the base year simulating their gradual evolution over time. The energy production mix for EU-25 is provided in Figure 3 while detailed data for each EU member state is provided in Table: 5 in APPENDIX I.

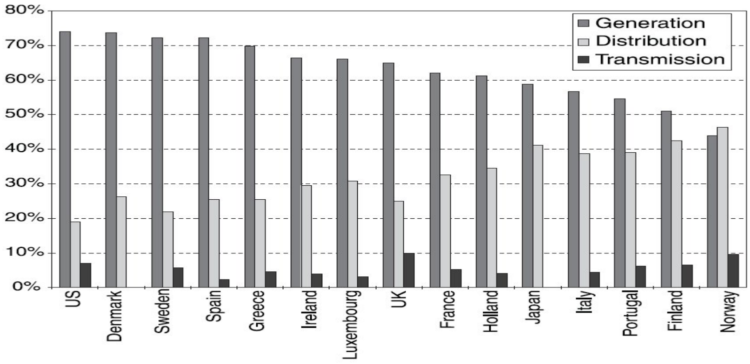
Figure 3: EU-25 technology mix of energy production (base year 1995).



2.2.2. Costs shares of transmission and distribution.

The input output flows of the electric power sector tabulated in the macroeconomic accounts are actually aggregates of two activities: electricity generation and transmission and distribution. Incorporation of energy technologies in the model requires the disaggregation of the SAM column that corresponds to the electric power sector and identification of the transmission and distribution sector.

Figure 4:Electricity generation, distribution and transmission cost shares.



Source: IEA

To split the aggregated energy sector to a T&D component and to a power generation component we utilized information related to the cost shares of transmission, generation and distribution, based on IEA and USA DOE reports. The generation cost accounts for over half of total cost and in most E.U. countries they account for over 60% while transmission costs range between for 5% and 10%.

2.3. Input output and bottom up data reconciliation.

The main difficulty in incorporating power producing technologies in a CGE model lies on the reconciliation between engineering and macroeconomic data. Integration of the two datasets is not straightforward since their construction is based on very different principles (i.e. the zero profit and market clearance conditions applied in the input output table should be made compatible with the energy conversion principles on which the energy balances are based). Additionally the reconciliation of the datasets should follow the model specification so as to facilitate its numerical calibration. In the rest of this section we present a calibration technique, used to minimise the deviation between the input output and the engineering data.

The electricity sector as it appears in GEM-E3 (and ideally down to the finest detail in input output tables) has been split into two different types of sectors: (i) generating sectors (*gen*), one for each technology type (ii) a remainder sector (*t&d*) broadly representing the provision of electricity services to consuming sectors (transportation, distribution, metering, network maintenance, system management etc.).

In order to disaggregate these sectors a mapping should be specified between the entries of the input output table and the engineering information retrieved from the technical databases. For this purpose we need to identify within the engineering database the following cost elements: (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. Then these cost elements are linked to the variables of the GEM-E3 model according to the following rationale: Annualised capital costs correspond broadly to operating surplus , Fuel costs correspond to the fuel input and variable operating and maintenance cost are mostly materials. Fixed operating and maintenance costs mostly represent wages and salaries paid to employees engaged in power generation (naturally independent of output).

Equations [1], [2] and [3] show how the engineering bottom up data collected is used in order to split the electricity sector into the two different types of sectors mentioned above (generation and transmission & distribution.

$$Qgen_r = Q_r \cdot (1 - sh\_td_r) \quad \text{and} \quad Qtd_r = Q_r \cdot sh\_td_r \qquad [1], [2]$$

$$Qet_{et,r} = Qgen_r \cdot mkt\_sh_{et,r} \cdot cst\_sh_{et,inp,r} \qquad [3]$$

where,
r refers to countries
et refers to energy technologies
inp are the fuel inputs of the energy technologies {agriculture, coal, oil, gas}.

Q_r is the total cost of electricity production, transmission and distribution provided by the input output table,

$Qgen_r$ is the cost of power generation ,

Qtd_r is the cost of electricity transmission and distribution,

$Qet_{et,r}$ is the technology specific cost of power generation,

sh_td_r is the share of transmission and distribution to total cost of electricity production,

$mkt\_sh_{et,r}$ is the market share of each energy technology and

$cst\_sh_{et,inp,r}$ is the cost structure of the energy technologies.

Table 3 depicts by way of example the split of UK energy sector using the bottom up engineering information and the assumptions related to the mapping of engineering variables and input output macroeconomic variables. This table provides four sets of information (i) the share data used to split the electricity sector to generation sector (*gen*) and to the transmission and distribution sector (*t&d*) (ii) the market share data used to split the generation sector production to individual production by technology (iii) the cost share data that were applied in order to compute the various inputs of each energy technology and (iv) the resulting deviations in capital and labour (marked in the circle). The labour and capital that each power generation technology and the transmission and distribution sector should employ (as this is suggested by the engineering data) exceeds the macroeconomic data of the UK input output table by 36% and 18% respectively. Similar incompatibilities occur to all E.U. member states although it ranges depending on the accuracy of the statistical input output and engineering data and the appropriateness on the assumptions made for the correspondence between the two datasets .

Table 3: UK energy sector dissagregation based on bottom up data .

Original IO energy sector			**Energy producing technologies**							**T&D Sector**	Total	Deviation
			COA	*GS2*	*OL1*	*NK1*	*BGT*	*HD1*	*WID*			
Coal	4327	Coal	4327								4327	0%
Oil	704	Oil			704						704	0%
Gas	2048	Gas		2048							2048	0%
Agriculture	0.02	Agriculture					0.02				0	0%
Materials	9379	materials								9379	9379	0%
		COA								46.3%	6649	
		GS2				market shares of technologies				19.6%	2814	
		OL1								5.2%	748	
		NK1								26.8%	3845	
		HD1				Technology cost structure				1.9%	276	
		WID								0.1%	17	
Capital	5500	Capital	2002	633	87	3357	0.01	267	16	375	6738	-18%
Labour	2709	Labour	1144	463	44	940	0.00	41	3	1594	4229	-36%

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. That means that the deviation of capital and labour (that in the table above stands to -18% and -36% respectively) should disappear while at the same time the market shares and the cost structures of the technologies should change as little as possible. Toward this end the methodology described in Figure 5 was applied (here it is presented in a generic form whereas the exact formulation is presented in the Appendix). This calibration technique cannot be applied uniformly since each country presents specifities that should be individually taken into account. 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.

The above problem has been formulated as a non linear problem where the flows are defined as decision variables and the parameters of the constraints are obtained from the IO table.

Figure 5: Mathematical description of the BUTD calibration technique.

$$\underset{y_1 \ldots\ldots y_n}{\text{Minimize}} \quad \sum_{j=K,L,M,F} \sum_{i=1}^{n} w_{j,i} \cdot \left[\ln\left(\frac{y_{j,i}}{\bar{y}_{j,i}} \right) \right]^2$$

$$\text{s.t.} \quad \sum_{ki} y_{ki} = K \quad \text{and} \quad \sum_{li} y_{li} = L \quad \text{and} \quad \sum_{mi} y_{mi} = Mat \quad \text{and} \quad \sum_{fi} y_{fi} = Fl$$

where,

$w_{j,i}$ are weights

$y_{j,i}$ are the flows shot within the optimization problem.

$\bar{y}_{j,i}$ the flows that correspond to the technological database.

K, L, Mat and Fl are capital, labor, materials and fuels constraints provided by the IO table.

The weights *w* used in the calibration model give the opportunity to put emphasis on different flows according to the importance of the variable or the value of the original information. If a particular flow is very significant in terms of defining a technology or if the numbers are very accurate a high *w* may be chosen. A differentiation of the weights is highly advisable – among other things because it helps overcome cases of over-determination[5].

Application of the above mentioned calibration technique in the U.K. matrix resulted in Table 4. It is clear that the capital and labor constraints were fully satisfied in the expense of markets shares (the market share of nuclear was reduced by 4% while there was an 1% increase in the market share of the oil conventional thermal and gas turbine combined cycle technology) and technology cost structures (i.e. capital and labor on nuclear technology register the highest reduction by 24% and 17% respectively).

Table 4: The balanced UK table.

	Energy producing technologies							**T&D Sector**	Total	Change from initial market share
	COA	*GS2*	*OL1*	*NK1*	*BGT*	*HD1*	*WID*			
Coal	4327								4327	
Oil			704						704	
Gas		2048							2048	
Agriculture					0.02				0	
materials								9379	9379	
COA								48%	6929	2%
GS2					market shares of technologies →			21%	2979	1%
OL1								6%	825	1%
NK1								23%	3332	-4%
HD1								2%	239	0%
WID								0%	19	0%
Capital	1719	561	81	2615	0.01	204	16	304	5500	
Labour	909	370	40	717	0.00	34	3	635	2709	
Capital	-14%	-11%	-7%	-22%	0%	-24%	0%	-19%		
Labour	-21%	-20%	-9%	-24%	0%	-17%	0%	-60%		
Change from initial cost structure										

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[5] The non-linear program described above could suffer from ill conditioning of the Jacobian around the optimal solution. This is an indication of flat slopes meaning that relatively big variations in the decision variables result into insignificant changes in the objective value. Loosely speaking this may mean that we have not specified enough the importance of different departures from the technical data thus allowing too much freedom to the calibration procedure in situations where many alternatives satisfy both the optimality conditions and the constraints of the problem.

2.4. GEM-E3 BUTD module technical specification.

The GEM-E3-BUTD model is a general equilibrium model that simultaneously represents all EU member states, linked through endogenous bilateral trade while the behavior of the rest of the world is exogenous. The sectoral coverage of the model has been increased so as to explicitly include power producing technologies. The optimal production behavior for the electricity sector is identical to the other sectors of the economy and can be represented in the primal or dual formulation.

The primal formulation is given by:

$$XD_i = \sum_j \left[\delta_{i,j}^{\frac{1}{\sigma}} \cdot X_{i,j}^{\frac{\sigma-1}{\sigma}} \cdot e^{-(1-\sigma)\cdot tpj\cdot t} \right]^{\frac{\sigma}{\sigma-1}}$$

$$X_{i,j} = XD_i \cdot \delta_{i,j} \cdot \left(\frac{P_i \cdot e^{-(1-\sigma)\cdot tp_j\cdot t}}{PX_{i,j}} \right)^{\sigma}$$

$$P_i \cdot XD_i = \sum_j PX_{i,j} \cdot X_{i,j} \qquad (\textit{zero profit condition})$$

where P_i is the output price of domestic production XD_i, $\delta_{i,j}$ are scale factors for the production factors $X_{i,j}$ (intermediate consumption, energy, capital and labour), $PX_{i,j}$ is the price of the factor j and σ is the substitution elasticity. The last factor in the equation reflects the technical progress that is embedded in the production factors (tp_j is the rate of technical progress embedded in production factor j).

The dual formulation is given by:

$$P_i = \sum_j \left[\delta_{i,j} \cdot PX_{i,j}^{1-\sigma} \cdot e^{-(1-\sigma)\cdot tp_j\cdot t} \right]^{\frac{1}{1-\sigma}}$$

$$X_{i,j} = XD_i \cdot \delta_{i,j} \cdot \left(\frac{P_i \cdot e^{-(1-\sigma)\cdot tp_j\cdot t}}{PX_{i,j}} \right)^{\sigma}$$

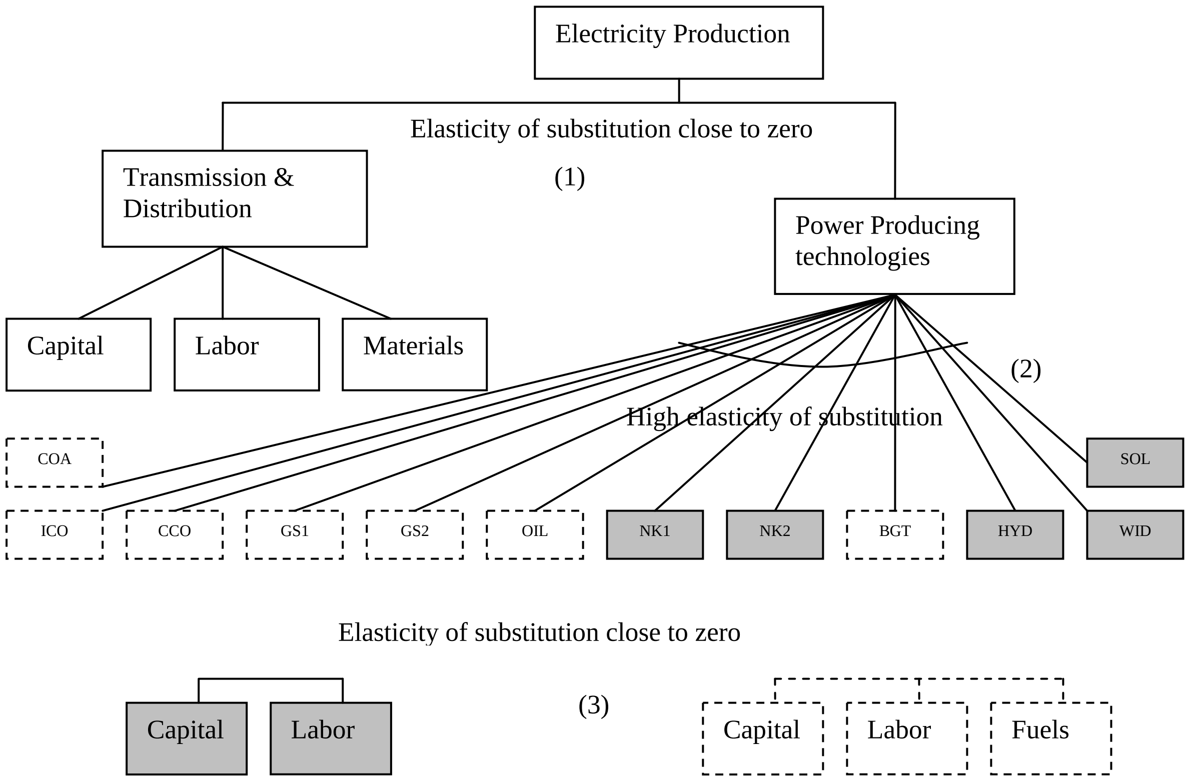
$$P_i \cdot XD_i = \sum_j PX_{i,j} \cdot X_{i,j} \qquad \textit{(zero profit condition)}$$

In the ***GEM-E3*** model, there is an additional constraint, namely that in the short term (i.e. within the period) the amount of available capital is fixed. This breaks the assumption about constant returns of scale, and the supply side of production is reflecting decreasing returns of scale. In both formulations, an equation for the equality between desired and existing capital is added and one of the (j+1) equations (j derived demand functions and the zero profit condition) is redundant: either the demand of capital is redundant and the zero profit condition serves to compute the rate of return on capital, the equilibrium on the good market determining the price of the good either the zero profit equation is suppressed and the equilibrium on the capital determines the rate of return on capital.

2.4.1. The electricity sector production in GEM-E3

Production functions in ***GEM-E3*** exhibit a nested separability scheme, involving capital (K), labour (L), energy (E) and materials (M) and are based on a CES neo-classical type of production function. The exact nesting scheme of production in ***GEM-E3***, has been selected to match available econometric data on KLEM substitution elasticities. Integrating the bottom up module in GEM-E3 implies that a new nesting production scheme particular to the electricity sector should be applied.

Figure 6: Electricity production nesting scheme



At the top level of the production function there is a CES aggregation of the transmission and distribution (*T&D*) bundle and the power generation bundle (*GEN).* At this level (1) the elasticity of substitution chosen is 0.1 since these activities are considered complementary. The power generation bundle is then a C.E.S. aggregate of a set of discrete power technologies. At the second (2) nesting level a high elasticity of substitution is chosen (2.5) allowing smooth shifts in the technology mix of power production. At the bottom level (3) of the production function are the inputs for the electricity technologies (capital and labor for renewables and nuclear and capital, labor and fuels for the rest). Elasticity of substitution is selected to be low at this level so as to ensure that the specific technology cost characteristics are preserved.

In GEM-E3 for introducing the nested CES function we adopt the dual formulation described above. The primal production function has the following form (for the1st nest):

$$XD_{ele} = \left[d_{td}^{\frac{1}{s}} \cdot \left(XD_{td}\right)^{\frac{s-1}{s}} + d_{gen}^{\frac{1}{s}} \cdot \left(XD_{gen}\right)^{\frac{s-1}{s}} \right]^{\frac{s}{s-1}}$$

where XD_{ele} is the domestic production of electricity, XD_{td} is the production of transmission and distribution, XD_{gen} is the aggregate power generation , s is the elasticity of substitution between XD_{td} and XD_{gen} . The d_{td} and d_{gen} are scale parameters calibrated using the bottom up data and the substitution elasticities:

$$d_{td} = \left(VSH_{td,ele}\right)^{s} \cdot \left(\frac{XD_{td}^{0}}{XD_{ele}^{0}}\right)^{1-s} \quad \text{and} \quad d_{gen} = \left(1 - VSH_{gen,ele}\right)^{s} \cdot \left(\frac{XD_{gen}^{0}}{XD_{ele}^{0}}\right)^{1-s}$$

where $VSH_{td,ele}$ and $VSH_{gen,ele}$ are the base year value shares of transport and distribution and aggregate power generation in total electricity production respectively.

The dual function representing the unit production cost is:

$$PD_{ele} = \left[d_{td} \cdot \left(PXD_{td}\right)^{1-s} + d_{gen} \cdot \left(PXD_{gen}\right)^{1-s}\right]^{\frac{1}{1-s}}$$

where PD_{ele} is the deflator in domestic electricity production and PXD_{gen} and PXD_{td} are the production unit costs of power generation and transmission and distribution respectively.

$$XD_{gen} = \left[\sum_{et}\left(d_{et}^{\frac{1}{s1}} \cdot XD_{et}^{\frac{s1-1}{s1}}\right) \cdot \right]^{\frac{s1}{s1-1}} \quad \text{and}$$

$$XD_{td} = \left[d_{kav,td}^{\frac{1}{s2}} \cdot \left(KAV_{td}\right)^{\frac{s2-1}{s2}} + d_{LEM,td}^{\frac{1}{s2}} \cdot \left(LEM_{td}\right)^{\frac{s2-1}{s2}}\right]^{\frac{s2}{s2-1}}$$

Where XD_{et} is power generation by technology, *et* is the set of energy technologies, *s1* is the elasticity of substitution between energy technologies and d_{et} is the share parameter calibrated based on the market share data and the *s1* substitution elasticity.

KAV_{td} is the volume of operating surplus employed in the transmission and distribution sector, LM_{td} is the aggregate volume of labor, electricity and materials used as input in this sector, d_{kav} and d_{lem} are share parameters and *s2* is the substitution elasticity between capital and the labor, electricity material bundle.

The dual formulation of XD_{gen} and XD_{td} is:

$$PXD_{gen} = \left[\sum_{et}\left(d_{et} \cdot PXD_{et}^{1-s1}\right) \cdot \right]^{\frac{1}{1-s}} \quad \text{and}$$

$$PXD_{td} = \left[d_{kav} \cdot \left(PKAV_{td}\right)^{1-s2} + d_{LEM} \cdot \left(PLEM_{td}\right)^{1-s2}\right]^{\frac{s2}{1-s2}}$$

Where PXD_{et} is the unit production cost of the discrete power producing technologies, $PKAV_{td}$ is the rate of return on capital in the transmission and distribution sector and $PLEM_{td}$ is the unit cost of the labour, electricity material bundle.

Optimal factor demand both in the transmission and distribution sector and the generation sectors is derived from Shephard lemma.

The derived demand for the Labour-Energy-Materials bundle is:

$$LEM_{td} = XD_{td} \cdot d_{lem,td} \cdot \left(\frac{PXD_{td}}{PLEM_{td}}\right)^{s2} \quad \text{and}$$

$$KAV_{td} = XD_{td} \cdot d_{kav,td} \cdot \left(\frac{PXD_{td}}{PK_{td}}\right)^{s2} \cdot e^{tgk_{td} \cdot (s2-1)}$$

Equation KAV_{td} gives the desired capital demand and will be used in the capital market equilibrium equation which derives the rate of return of capital of capital PK_{td} as the equilibrium price that equalises demand and supply of capital (the same applies for the energy technologies capital demand) .

Similar formulas can be derived for the other levels of the nesting scheme of the production function, always linking the demand for a factor at a lower level of the nesting scheme to the bundle to which it belongs, with different substitution elasticities at each level. This gives finally a cost-minimising demand for each production factor.

2.4.2. Investment Demand

The demand for capital for the next year, which fixes the investment demand of the firms, is determined through their optimal decision on factor inputs for the next year with the framework described above. Having identified electricity production technologies as distinct sectors in the input output tables we are able to model their investment decision based on the Ando-Modiglianni formula. In particular the desired demand for capital (K_{fut}) (as derived from long run cost minimisation under the production function constraint) is a function of the optimal long run cost of capital and the expected values for the volume of production and the production deflator. The optimal long-run cost of capital derived according to Ando-Modigliani formula[6], is equal to the investment deflator (*PI*), times the real interest rate (*r*) augmented by the depreciation rate (d)

$$PK_{opt} = PINV \cdot (r+d)$$

and the desired capital for the next year (K_{fut}) is

$$\frac{K_{fut}}{Y_{\exp}} = \delta_{k,PR} \cdot \left(\frac{PD_{\exp}}{PK_{opt}} \right)^{\sigma}$$

The exact formulation of the capital demand function above, depends on the type of expectations that producers are assumed to have concerning the evolution of the economy and the future prices. In the ***GEM-E3***, these are linked to the expected rate of growth of the economy and the current price level. Although the exact formulation of the expectations affects the quantitative results of the simulations of ***GEM-E3***, the qualitative ones remain unaffected.

The comparison of the available stock of capital in the current year with the desired one determines the volume of investment decided by the firms. Given a partial adjustment mechanism and the fixed replacement rate d, the derived investment demand of the firm is

$$INVV_{PR} = m \times (K_{PR,fut} - (1-d) K_{PR,fixed})$$

or replacing future capital by the equation determining the desired capital

$$INVV_{PR} = m \times KAV_{PR} \cdot \left[\left(\frac{PK_{PR}}{PINV_{PR} \cdot (r+d)} \right)^{\sigma} \cdot (1+STGR) \cdot e^{tgk(\sigma-1)} - (1-d) \right] \quad (1)$$

where $PINV_{PR}$ is the cost of investments and $STGR_{PR}$ is the expected growth rate of the sector.

The next period capital stock is given by the equation:

$$KAVC_{PR} = (1-d)^T \cdot KAV_{PR} + \left(\frac{1-(1-d)^T}{d} \right) \cdot INVV_{PR} \quad (2)$$

---

[6] See Ando, Modigliani et.al (1974).

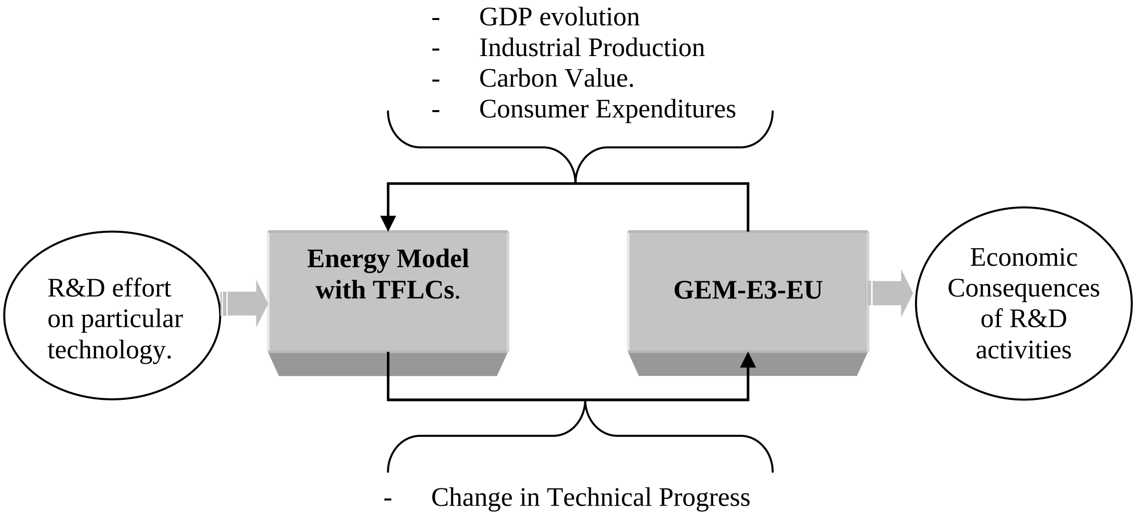
where T is the length of the period in the model.Since the capital is fixed within each period, the investment decision of the firms affects their production frontier only in the next period. Finally the investment demand of the power technologies is transformed into a demand by product, through fixed technical coefficients, derived from an investment matrix by product and ownership branch.

3. Development of energy model with TFLC.

3.1. Two factor learning curves sub model.

An energy model that incorporates two factor learning curve mechanism was developed. This model is able to identify the impacts of learning by doing and government R&D spending on the cost and performance of the energy producing technologies. The results of the energy model are then translated into changes in the technical progress parameters of the GEM-E3-EU model (Figure 7).

Figure 7: Model interaction mechanism.



The energy model is self contained and identifies the following energy producing technologies:

- (Biomass Gasification + GTCC, Decentralised PV, Molten Carbonate Fuel Cells, Small Hydro, Solar Thermal, and Wind technologies
- Advanced Thermodynamic Cycle, Coal Conventional Technologies, Integrated Coal Gasification, Lignite Conventional Technology, and Pulverised Fuel Supercritical Coal
- Oil Conventional Technology, and Oil in GTCC
- Combined Heat and Power, Gas Conventional Technology, and Gas in GTCC
- New Nuclear Design and Nuclear Conventional LWR.

The capital cost of each technology is calculated using two-factor learning curves. In particular:

$$\text{capital cost} = \text{capital cost}_{t-1} \cdot \left(\frac{\text{capacity}_{t-1}}{\text{capacity}_{t-2}} \right)^{alpha} \cdot \left(\frac{\text{cumulative R \& D}_{\ t-1}}{\text{cumulative R \& D}_{\ t-2}} \right)^{beta} \qquad [1]$$

$$alpha = \frac{capelfac}{1 + \exp\left[200 \cdot \frac{|y| - 20}{20} \right]} \qquad [2]$$

$$beta = \frac{erda \cdot \exp[erdb \cdot \ln(\text{cumulative R \& D})]}{1 + \exp\left(200 \cdot \frac{|y| - 20}{20} \right)} \qquad [3]$$

$$y = \frac{flv}{flv - \text{capital cost}_{t-1}} \qquad [4]$$

Where,

flv: the minimum cost of technology.

capelfac: learning by doing elasticity.

erda, erdb: learning by research elasticity.

The learning-by-doing component in [1] is given by: the growth rate of capacity of the technology raised to a power [2] that is based on the floor values of the capital costs, and the capital costs of the previous year.

The learning-by-research component in [1] is given by: the growth rate of cumulative R&D for each technology raised to a power [3] that is based on the floor values of the capital costs, the capital costs of the previous year, and the cumulative R&D for each technology.

Both Fixed Operating & Maintenance (FOM) and Variable Operating & Maintenance (VOM) costs of each technology are linked to the growth rate of capital costs. The technology cost of each technology for the production of electricity is based on the capital cost, FOM and VOM costs, the price of the fuel used by each technology, and its efficiency.

Electricity production from each technology depends on the technology cost of each technology for the production of electricity and the generating cost of electricity.

The model identifies four energy forms for final demand (coal, oil, natural gas, and electricity) and five demand categories (electric and non-electric industrial, electric and non-electric residential/commercial, and transport).

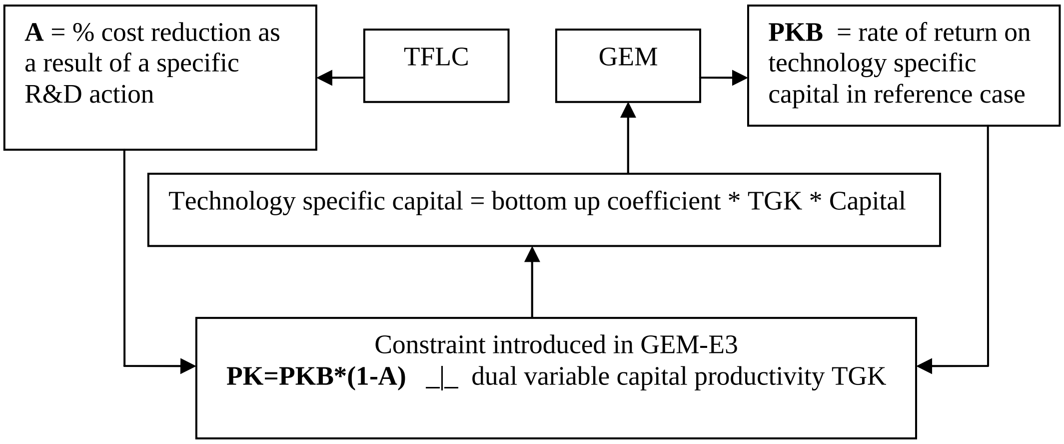
Prices are computed for eight energy forms for final demand (coal for industry, heavy fuel oil, light fuel oil, gasoline, natural gas for industry and residential/commercial, and electricity for industry and residential/commercial users).

3.1.1. Linking the TFLC satellite model with the GEM-E3 model.

Integration of the bottom up module provides GEM-E3 with a mechanism whereby technology costs are used to establish an energy substitution surface. In order to enable a feedback to the two factor learning curve a reverse mapping will also have to be modelled whereby an equilibrium point on the energy substitution surface is translated into capital costs reductions on specific technologies. In particular the estimated R&D effect on the capital cost of each electricity producing technology should be translated directly to technical progress changes compatible with the GEM-E3 production function specification. Toward this end it was assumed that the cost of capital in the GEM-E3 model should be fixed at levels indicated by the TFLC model. Then capital market equilibrium will be achieved by endogenising the technical progress of capital.

The algorithm adopted to elaborate the joint operation of the two models is presented in Figure 8.

Figure 8: TFLC and GEM-E3-BUTD link.



4. Equipment manufacture sector effects.

The linkages described in Figure 8 enable the execution of a number of simulations: notably they allow to examine the impact of R&D actions on specific technologies on the investment choices of power generators. In this way the analysis can be extended to the exploration of possible benefits to the E.U. power generating sector arising from additional R&D on specific technologies in the presence of alternative climate policy stances.

On the other hand R&D in power generation technologies is not usually undertaken by the power generating sector in order to obtain the above mentioned benefits. The agents carrying out most of this type of R&D belong to the broad category of equipment manufacturers. In this sense most R&D actions are motivated by a desire to increase profitability in this sector (or at least avoid reduction o such profitability).

Considerations of such profitability (or survival of specific firms) lie outside the scope of general equilibrium analysis which assumes zero profits as an equilibrium condition. In order to examine the economic implications of R&D actions it is important to be able to measure at least any gains in market share (i.e. output) resulting from such actions. The specification adopted is in itself unable to simulate such output changes. Though the R&D intervention on specific technologies will result in the increased adoption of these technologies within the EU economic space, it is unclear what the net effect of such a development would be with respect to additional sales on equipment. The technologies the attractiveness of which is enhanced by R&D may simply replace other technologies and the net effect may even be negative. An obvious way to include some output effects is to model the impact of the cost reduction on export sales of equipment.

. The specification of the model discussed so far shows that R&D policies operate through reductions in capital cost in the power sector while the economic benefits accrue to power and electricity using sectors. In order to capture potential benefits to the equipment manufacturing industry in this direction the ‘Equipment Manufacturing Industry’ has been split into two sub-sectors:

(i) one selling within E.U. exclusively and
(ii) one selling outside E.U. exclusively.

The main assumption adopted for this sectoral dissagregation is that the two sectors will have identical input structures. This disaggregation helps translate the R&D induced impact (coming from TFLC model) in the following ways:

- By affecting the ‘domestic sub-sector’ only through decisions of EU power producers.
- By inducing weighted (depending on the importance of technology in total equipment) improvement in the factor productivity of the ‘exporting sub-sector’.

This approach is proposed because it avoids an unreasonable spillover of the technology specific R&D impact on equipment manufacturing while it generates a competitive advantage effect. The main disadvantages of this approach are its asymmetric treatment of the two sectors and the constraint that the modified GEM-E3 model can only be used to perform simulations of R&D portfolio policy at EU wide level.

The disaggregation of the equipment manufacture sector was based on the share of power equipment industry in the equipment manufacture industry. The respective data on value added and sectoral production were extracted from the EUROSTAT database. Regarding the bilateral trade of this sector it was assumed an identical structure to the aggregate equipment manufacturing industry.

5. APPENDIX I

Table: 5 Technology mix of energy production for E.U. members (%) 1995.

	Coal conventional thermal	**Gas conventional thermal**	**Gas turbine combined cycle**	**Oil conventional thermal**	**Nuclear (2n -3rd)**	**Hydro electric**	**Wind**	**Photovoltaics**
	(COA)	*(GS1)*	*(GS2)*	*(OL1)*	*(NK1)*	*(HD1)*	*(WID)*	*(DPV)*
Austria	7.9	9.4	8.4	3.9	0.0	70.4	0.00	0.01
Belgium	22.5	4.5	13.1	1.8	56.4	1.7	0.01	0.00
Czech	73.4	0.0	1.7	1.0	20.2	3.8	0.00	0.00
Germany	54.6	5.3	4.2	1.7	28.9	5.0	0.32	0.01
Denmark	76.6	5.7	4.4	9.9	0.0	0.1	3.29	0.00
Estonia	96.5	2.2	0.1	1.2	0.0	0.0	0.00	0.00
Greece	69.2	0.2	0.0	21.4	0.0	9.1	0.08	0.00
Spain	39.8	0.0	3.0	8.8	33.5	14.8	0.16	0.01
Finalnd	20.0	3.1	11.0	2.8	37.7	25.3	0.02	0.00
France	4.9	0.3	0.9	1.6	76.8	15.5	0.00	0.00
Hungary	26.8	10.8	5.0	15.6	41.4	0.5	0.00	0.00
Ireland	44.3	11.0	21.5	16.9	0.0	6.1	0.10	0.00
Italy	10.2	3.5	17.8	50.9	0.0	17.7	0.00	0.01
Lithuania	0.0	1.6	0.1	7.7	85.2	5.4	0.00	0.00
Latvia	0.0	13.1	0.4	10.8	0.0	75.7	0.00	0.00
Netherlands	32.9	1.9	54.7	4.9	5.1	0.1	0.40	0.01
Poland	95.0	0.0	1.1	1.1	0.0	2.8	0.00	0.00
Portugal	41.6	0.0	0.1	32.0	0.0	26.2	0.05	0.01
Sweden	1.6	0.0	0.9	2.7	48.0	46.8	0.07	0.00
Slovenia	34.3	0.0	0.2	2.1	37.8	25.6	0.00	0.00
Slovakia	24.5	7.5	1.8	2.8	43.5	19.9	0.00	0.00
United Kingdom	46.3	0.0	19.6	5.2	26.8	1.9	0.12	0.00

6. APPENDIX II

The objective function that should be minimized is [1]:

$$obj = w1_r \cdot obj1_r + \sum_{et}\left(w2_{et,r} \cdot obj2_{et,r}\right) + w3_r \cdot obj3_r + w4_r \cdot obj4_r + \sum_{et}\left(w5_{et,r} \cdot obj5_{et,r}\right) + \sum_{et}\left(w6_{et,r} \cdot obj6_{et,r}\right) + \sum_{et}\sum_{inp}\left(w7_{et,r,inp} \cdot obj7_{et,r,inp}\right). \tag*{[1]}$$

The constraints are:

$$obj1 = \left[\ln\left(\frac{gen\_td_r}{gen\_td\_0_r}\right)\right]^2 \tag*{[2]}$$

$$obj2 = \left[\ln\left(\frac{gen\_et_r}{gen\_et\_0_r}\right)\right]^2 \tag*{[3]}$$

$$obj3 = \left[\ln\left(\frac{lab\_td_r}{lab\_td\_0_r}\right)\right]^2 \tag*{[4]}$$

$$obj4 = \left[\ln\left(\frac{cap\_td_r}{cap\_td\_0_r}\right)\right]^2 \tag*{[5]}$$

$$obj5 = \left[\ln\left(\frac{lab\_gen_r}{lab\_gen\_0_r}\right)\right]^2 \tag*{[6]}$$

$$obj6 = \left[\ln\left(\frac{cap\_gen_r}{cap\_gen\_0_r}\right)\right]^2 \tag*{[7]}$$

$$obj7 = \left[\ln\left(\frac{fuel_r}{fuel\_0_r}\right)\right]^2 \tag*{[8]}$$

$$\sum_{et} gen_{et,r} = gen\_td_r \tag*{[9]}$$

$$ele_r = \sum_{et} gen_{et,r} + lab\_td_r + cap\_td_r + mat_r \tag*{[10]}$$

$$gen_{et,r} = \sum_{inp} fuel_{et,inp,r} + cap\_gen_r + lab\_gen_r \qquad [11]$$

$$\sum_{et}(cap\_gen) + cap\_td = cap\_ele \qquad [12]$$

$$\sum_{et}(lab\_gen) + lab\_td = lab\_ele \qquad [13]$$

$$\sum_{inp}\left(fuel_{inp}\right) = \sum_{inp}\left(fuel\_0_{inp}\right) \qquad [14]$$

where,

r: are the EU member states

et: are the energy technologies

inp : are the fuel inputs (agriculture, coal, oil, gas).

$w_1, w_2, w_3, w_4, w_5, w_6, w_7$: are the weights (*parameters*).

lab_gen, cap_gen : are the labour and capital employed by the electricity producing sector (*variables*).

lab_td, cap_td : are the labour and capital employed by the transmission and distribution sector (*variables*).

lab_et, cap_et : are the labour and capital employed by the energy technologies (*variables*).

fuel: are the fuels used by the energy technologies (*variable*)

mat: are the materials used by the transmission and distribution sector (*parameter*).

Note: all symbols ending with _0 indicate parameters.

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