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REPORT ON MODEL COUPLING AND HYBRID MODELLING

DELIVERABLE 2.2

Advanced Model Development and Validation for the Improved Analysis of Costs and Impacts of Mitigation Policies

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E3M-LAB, ECONOMY – ENERGY – ENVIRONMENT MODELLING LAB

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INTRODUCTION

The objective of this task is threefold:

i) To facilitate the process of splitting the electricity sector of GTAP to individual power generation technologies
ii) To improve the representation of energy transactions in IO tables
iii) To develop a methodological approach that will take advantage of the energy bottom-up data and allow to introduce bottom-up modules in CGE (top-down) models

Reaching these objectives helps in reducing the gap among top-down macroeconomic CGE models and bottom-up energy system models. Towards this end E3M-Lab has developed an automated energy split routine that collects statistics from readily available datasets and it performs the split of the power supply sector of GTAP into a transmission and distribution (T&D) part and individual power generation technologies. In addition the energy taxes and subsidies output from Work Package 3, Task 3.2 “Energy prices and subsidies” has been used in order to improve the calibration procedure of CGE models regarding energy transactions. The final outputs of this task are an energy split routine written in GAMS and a proposed methodology for introducing a detailed representation of the power generation system in a top-down modelling framework like CGE models.

This report provides a detailed documentation and technical guide on the energy split routine and enhanced energy transactions calibration. The report also provides a detailed overview of the data used and the methodology developed so as to take full advantage of the extended database compiled. The hybrid modelling methodology is presented in detail in the last section of this report. These extensions have been included in the new version of the GEM-E3 model and alternative model runs have been made in order to test the properties of the proposed methodology and the new calibration of energy transactions.

In this task a number of other modelling teams have participated in evaluating and using the different outputs of the task. In particular the following models and respective modelling teams have received the energy split code and the methodological documentation on hybrid modelling: UCAR (iPETS), IMACLIM (CIRED) and CGE-UCL (UCL). E3M-Lab has finalised the modelling routine following feedback from the partners on draft versions of the code circulated for comments.

The report starts with a user manual of the energy split routine that discusses the approach used to split the sectors, the final dataset constructed and its main advantages. The next section provides a brief comparison of the power generation splitting routine proposed with a recent methodology implemented for the construction of the GTAP-Power database. Then the report continues with a literature review on hybrid modelling focusing in the representation of power generation in CGE models. Following this part, the report continues with the presentation of proposed alternative modelling approaches for hybrid modelling, of the simulation results that illustrate the properties of these approaches and the extended dataset[1].

EXTENDING THE ENERGY REPRESENTATION IN IO TABLES

DATA REQUIREMENTS

The building block of CGE models is the social accounting matrices (SAMs) that represent flows of all economic transactions that take place within an economy (regional or national) in a given time period. Although these matrices can be very detailed[2], the electricity producing sector is always aggregated and there is no information on discrete power producing technologies (Figure 1). The lack of detailed representation of the electricity sector constitutes a barrier in modelling realistically the sector in CGE models as it is usually modelled by a representative firm (in this case any power mix transformation is captured by the elasticity of substitution i.e. substitution of fuels with capital reflects the increased use of RES).

The main difficulty in splitting the electricity sector to its components lies on the reconciliation of heterogeneous datasets like engineering, energy balances and macroeconomic datasets. Integration of the three 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 (IO) table should be made compatible with the energy conversion principles on which the energy balances are based).

(i) The datasets required to make the split of the electricity sector are the following:
(ii) Input Output (IO) tables
(iii) Energy Balances (to calculate the market shares and energy consumption by industry and power generation technologies)
(iv) Engineering databases (to calculate the cost structure of each power generation technology)
(v) Energy statistics (to calculate the share of T&D in total power generation sales)

The following sections present the data sources and key assumptions made to perform their reconciliation with the IO statistics. The power generation technologies considered are presented in Table 1.

---

[1] The complete energy split routine is also uploaded in the PIK FTP server to be freely downloaded. Databases with copyright are not included (i.e. GTAP 9, IEA etc.)

[2] The Input Output tables published by Eurostat refer to a 59 sectoral aggregation whereas those from GTAP to 57 and in WIOD 35.

Figure 1: Components of aggregate power supply sector in IO table

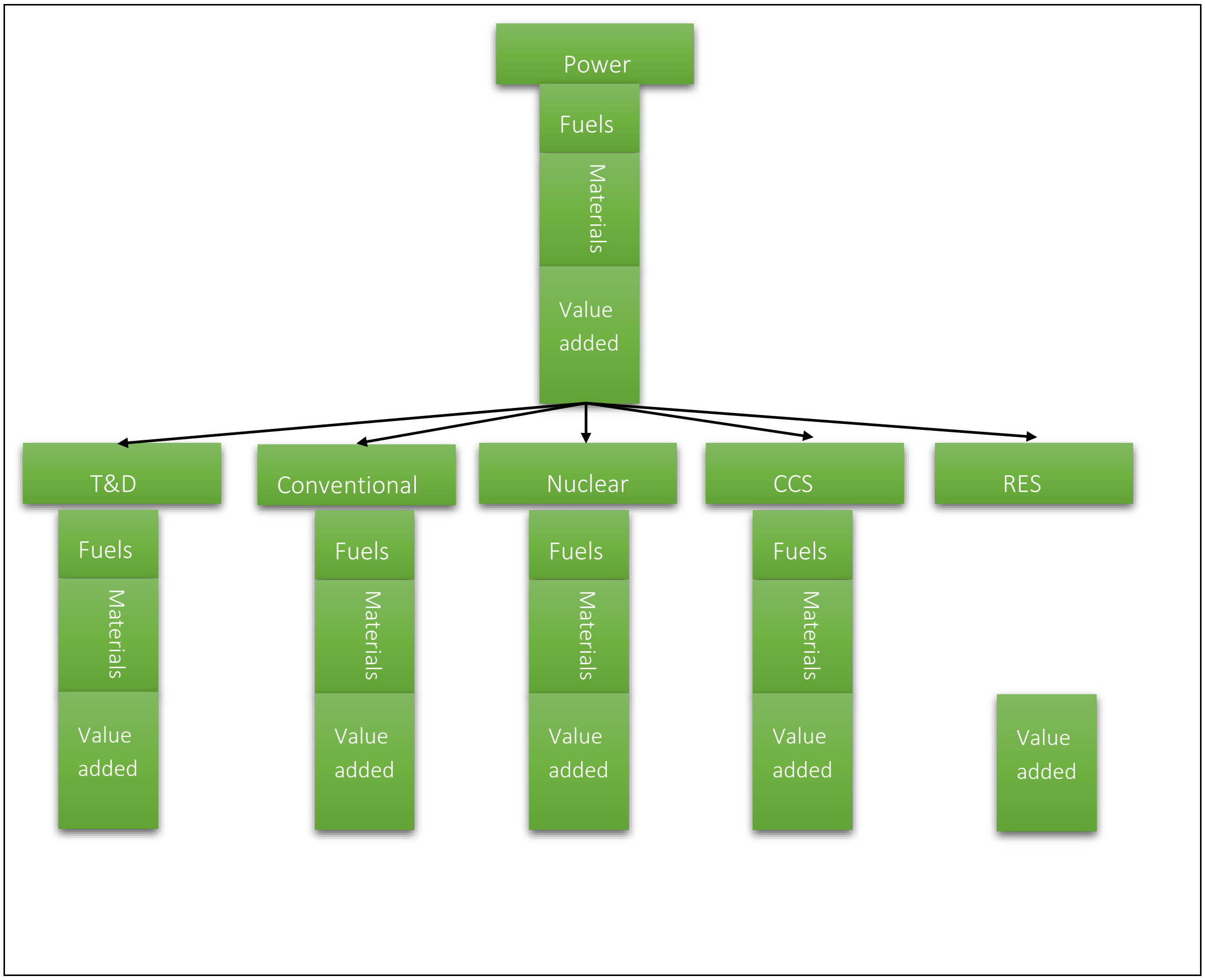


Table 1: Electricity producing technologies represented in the extended IO table

No	Name	Description
1	COA	Coal fired
2	GSS	Gas fired
3	OLL	Oil fired
4	NUC	Nuclear
5	BMS	Biomass
6	HYD	Hydro
7	WND	Wind
8	PVV	PV
9	WST	Waste
10	GTH	Geothermal
11	TWV	Tidal wave
12	STP	Solar thermal

13	CCS	Coal fired with CCS
14	GCS	GAS fired with CCS

GENERATION COSTS AND COST STRUCTURE

The technical database that has been used to calculate the generation costs and cost structure of each technology is the TECHPOL II dataset. The type of data extracted from the database are presented in Table 2.

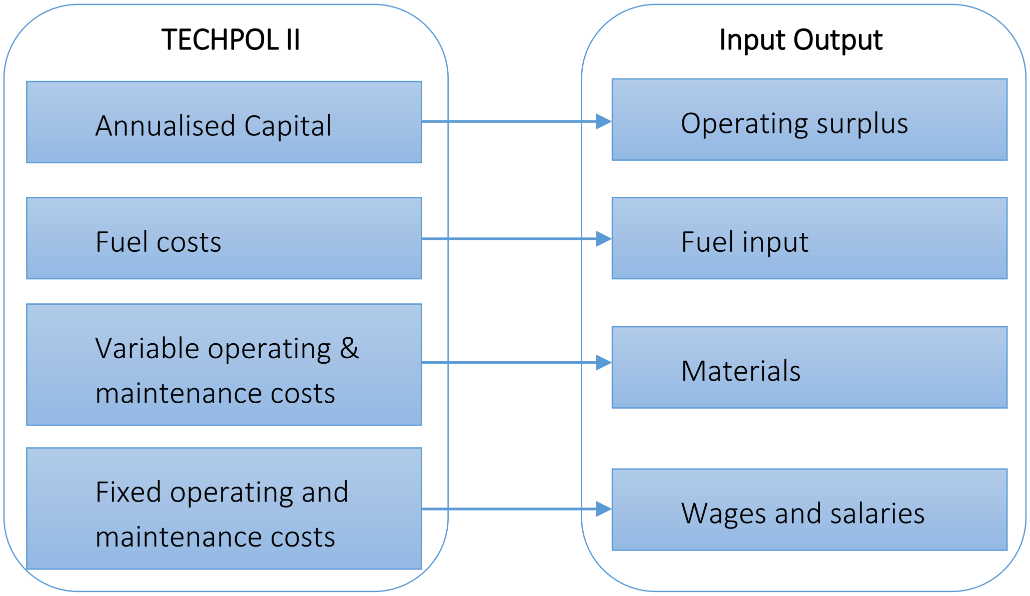
Table 2: Data elements extracted from the TECHPOL II database

Type	Unit
Overnight cost	€2010-kW
Technical lifetime	years
Construction time	years
Fixed O&M	€-kW
Variable O&M	€-MWh
Load factor	%
Electrical efficiency	%
Thermal efficiency	%
Decommission share	%

The first step in performing the energy split is to specify a mapping between the entries of the IO table and the engineering information retrieved from the TECHPOL II database. For this purpose the following cost elements are identified from the engineering database:

(i) Capital cost
(ii) Fixed operating and maintenance cost
(iii) Fuel cost
(iv) Other variable operating and maintenance costs

Then these cost elements are linked to the IO table following the rationale illustrated below:



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 into three main categories:

(i) Investment costs
(ii) Operating and maintenance costs
(iii) Fuel costs.

The technologies incorporated in the IO table are classified in two main groups:

a. Those existing in the base year and their market penetration is assumed to be mature:
   - Coal conventional thermal
   - Gas conventional thermal
   - Oil conventional thermal
   - Nuclear
   - Hydroelectric
b. Those with incomplete penetration rates:
   - Biomass
   - Wind
   - PV
   - Tidal wave
   - Solar thermal power plant
   - CCS

This distinction in mature and new technologies is made in order to assign marginal market shares in these technologies already in the base year.

The total production cost (*tpc*) consists of:

$$tpc = kct + fom + vom + fct \qquad [1]$$

where *kct* is the capital cost, *fom* is the fixed operating & maintenance costs, *vom* is the variable operating & maintenance costs and *fct* is the fixed costs. The capital costs are computed as:

$$kct = \frac{tic}{\frac{(1+drt)^{tlf}-1}{drt \cdot (1+drt)^{tlf}}} \qquad [2]$$

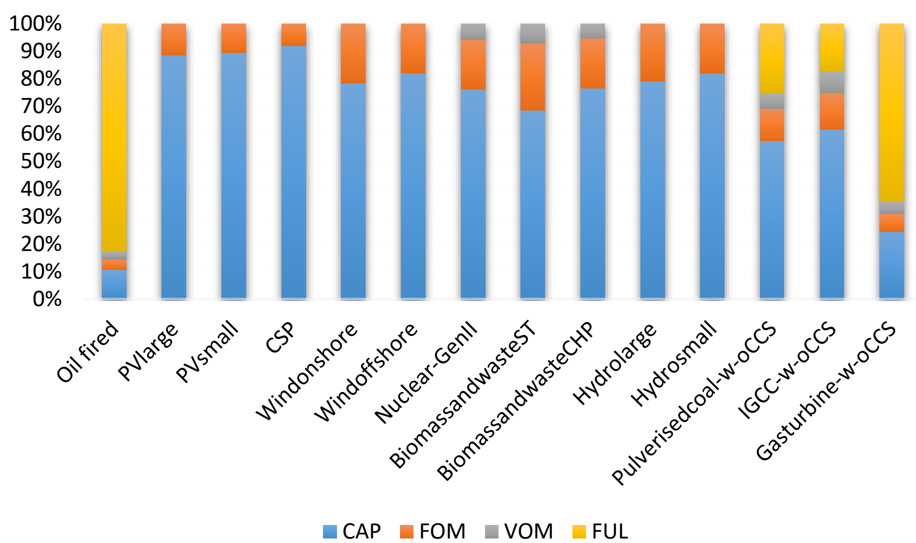
where *drt* is the discount rate, *tlf* is the technical lifetime and *tic*: is the total investment cost which is given by:

$$tic = \frac{oic \cdot (1 + dsh \cdot e^{drt \cdot tlf})}{\frac{cnt \cdot ((1+rir)^{cnt}-1)}{(1+rir)^{cnt}}} \qquad [3]$$

where *oic* is the overnight investment cost, *dsh* is the decommissioning share and *cnt* is the construction time.

The universal cost structure of each technology as derived from the TECHPOL II database is presented in Table 3.

Table 3: Electricity production cost shares.



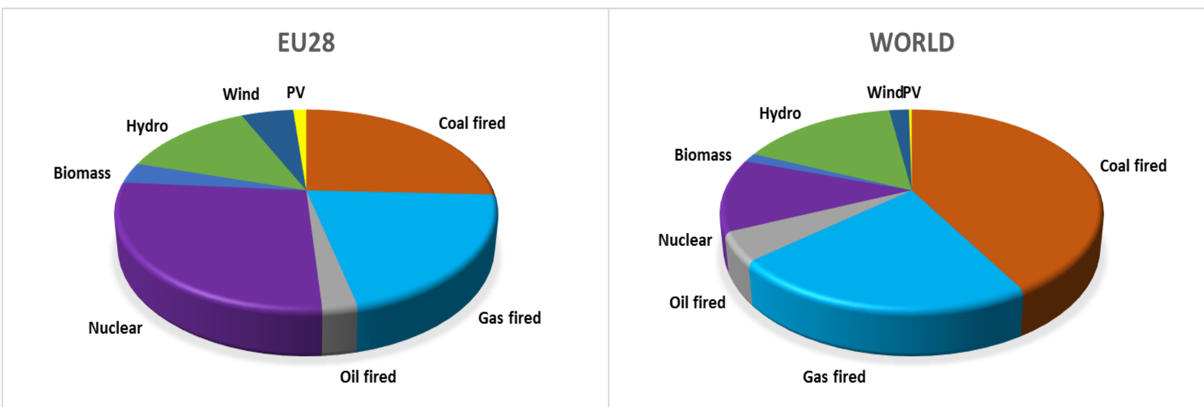
Source: Calculations based on TECHPOL II database

MARKET SHARES

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. Hence in the development of the extended IO table small marginal values (below the row and column balancing threshold) have been introduced for the new power producing technologies.

The IEA database has been used so as to obtain detailed data on energy balances (in volume) and calculate the respective market shares. The energy production mix for EU28 and the world are provided in Figure 2.

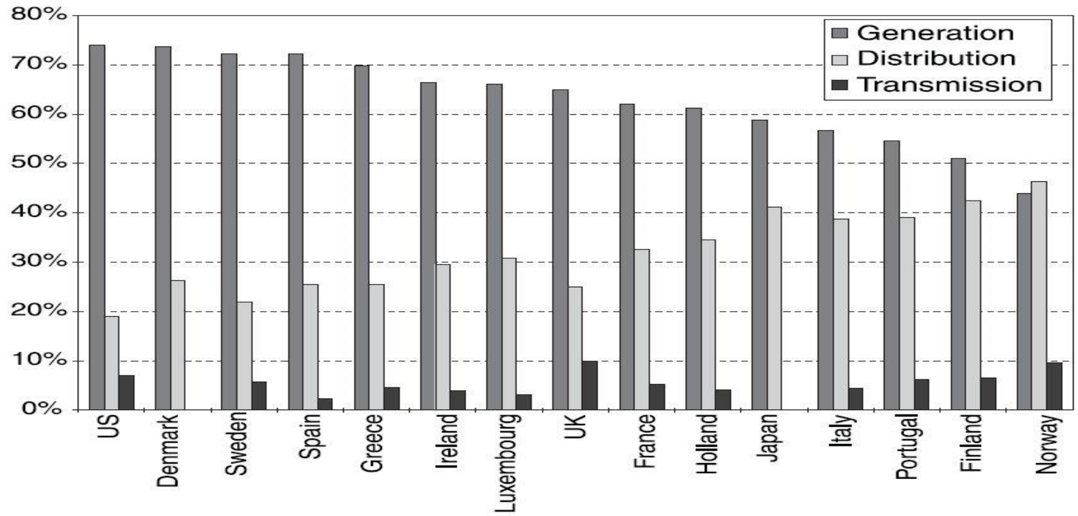
Figure 2: Technology mix of energy production for EU28 and the World



COSTS SHARES OF TRANSMISSION AND DISTRIBUTION

The IO flows of the electric power sector tabulated in the macroeconomic accounts are actually aggregates of two activities: i) electricity generation and ii) 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 3: 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 used 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 EU countries they account for over 60% while transmission costs range between 5% and 10%.

THE ENERGY SPLIT ROUTINE

Since CGE models are calibrated on Social Accounting Matrices it is reasonable to keep the macroeconomic data constant and adjust the market and cost shares of the power producing 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 IO table. That means that any deviation on materials, capital and labour implied by the inclusion of bottom-up data in the IO tables 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 a balancing routine has been applied. An illustration of the methodology used is provided in Figure 4 (here it is presented in a generic form whereas the exact formulation is presented in the following subsections). This calibration technique is applied uniformly in all GTAP countries. Country specificities, where for example there are cases where the IO 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, are handled by the routine.

The 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.

Figur

Minimize (y)

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

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

$w_{j,i}$ 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 balancing routine 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, as it helps overcome cases of over-determination[3].

FILE STRUCTURE

The routine files are summarized in Table 4 and discussed in brief below.

Table 4: Files used in the energy disaggregation routine

File name	Description
a_NRGsplit_start.gms	Initiating file which loads the data, the routine and reporting files
b_NRGsplit_GTAPIOt.gms	File including the routine for the construction of the IO tables based on *GTAP* data
c_NRGsplit_IEAGTAP.gms	File including the routine to load and aggregate the *GTAP* and *IEA* data
d_NRGsplit_TECHPOLII.gms	File loading the *TECHPOL II* data and the routine for the

[3] 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.

	calculation of the power generation production cost and structure
e_NRGsplit_IEAEBAL.gms	File loading the *IEA* data
f_NRGsplit_BUPG.gms	File including the routine for the bottom-up representation of the power generation technologies
g_NRGsplit_ENEP.gms	File splitting the IO in volumes and energy prices
h_NRGsplit_Report.gms	Reporting code file

In the GMS file named *a_NRGsplit_start* the working directory is defined and the GMS files that load the data from the different datasets (GTAP v.9, IEA, TECHPOL II) are called. In this file are also loaded the GMS files that include the routine for the construction of the IO tables and their extension so as to include a detailed representation of the different energy technologies. In this file it is last loaded the GMS file setting out the reporting routine. *a_NRGsplit_start* file loads a set of GMS files as follows:

- *b_NRGsplit_GTAPIOt.gms* file includes the code for the construction of the IO tables based on the GTAP v.9 database. The routine codified here initiates with the definition of the sets used. This is followed by appropriate mapping of model sectors and countries/regions to the *GTAP* sectors and countries/regions respectively. After loading the *GTAP* data a normalization of the national transport margins to the total international transport margins is undertaken. In the last step in this file it is undertaken the construction of the IO table based on GTAP data.
- *c_NRGsplit_IEAGTAP.gms* file loads and aggregates the GTAP and IEA data.
- *d_NRGsplit_TECHPOLII.gms* file loads the *TECHPOL II* and IIASA energy prices (IEA dataset) data and it calculates the power generation cost and production structure. Here investment, capital, fuel, fixed, variable and total costs are calculated. The detailed algebraic formulation of these calculations follows in the section below.
- *e_NRGsplit_IEAEBAL.gms* file loads the energy balances from the *IEA* database. For countries for which data are not available figures are estimated based on the world average percentage structure.
- *f_NRGsplit_BUPG.gms* file includes the routine for the breakdown of the electricity production to different technologies and the split of the IO flows. The detailed algebraic formulation is presented in the following section.
- *g_NRGsplit_ENEP.gms* file includes the routine which disaggregates the IO figures in volumes and energy prices.
- In the last sequential file named *h_NRGsplit_Report.gms* the steps used for the reporting of the bottom-up IO tables are loaded in the routine.

ALGEBRAIC FORMULATION OF THE ENERGY SPLIT ROUTINE

POWER GENERATION PRODUCTION AND COST STRUCTURE

In *d_NRGsplit_TECHPOLII.gms* file, cost structure is formulated in detail for each power generation technology type by cost component (fixed, variable, capital, investment and fuel cost). Data are obtained from the TECHPOL II database. Appropriate currency and unit conversions are made where necessary. The cost formulation is summarized in the following subsections.

COST STRUCTURE

Total investment cost calculations take into consideration total capital invested, the discount rate, the technical lifetime of the project and the construction time required. Total investment cost is defined by power generation technology, and it is given by the following equation:

$$\mathrm{tic}_{pg} = oic_{pg} \cdot \frac{(1 + dsh_{pg} * e^{-drt \cdot tlf_{pg}})}{\left[\frac{(1+rir)^{cnt_{pg}-1}}{rir \cdot (1+rir)^{cnt_{pg}}}\right]} \cdot cnt_{pg} \quad [4]$$

where:

pg: Power generation technology type

tic_{pg}: Total investment cost in Euro per kilowatt (Kw)

oic_{pg}: Overnight investment cost in Euro per Kw

dsh_{pg}: Decommission share

drt: Discount rate

tlf_{pg}: Technical lifetime

rir: Real interest rate

cnt_{pg}: Construction time (in years)

CAPITAL COST

Capital cost by power generation technology is given by:

$$\mathrm{kct}_{pg} = \frac{tic_{pg}}{\frac{1 + drt^{tlf_{pg}-1}}{drt \cdot (1 + drt^{tlf_{pg}})}} \quad [5]$$

where:

kct_{pg}: Capital cost in Euro per Megawatt hour (MWh)

Capital cost is calculated in US dollars per MWh as follows:

$$\mathrm{techpol\_kct}_{pg} = \frac{kct_{pg}}{lfc_{pg}} \cdot \frac{1000}{yhr} \cdot exr \quad [6]$$

where:

$\mathrm{techpol\_kct}_{pg}$: Capital cost in US dollars per MWh

yhr: Hours in a year (8760)

exr: Exchange rate, US dollars to Euro (set to 1.3)

FUEL COST

For the calculation of the fuel costs by power generation technology, IEA data on prices have been used. For the estimation of the fuel cost Gigajoules (GJ) are converted to MWh. Fuel cost is given by the following equation:

$$\mathrm{techpol\_fct}_{pg} = \sum_{pcat} \left(\frac{iea\_prices_{pcat} \cdot conGjMwh}{eel_{pg}}\right) \quad [7]$$

where:

$\mathrm{techpol\_fct}_{pg}$: Fuel cost in US dollars per MWh

iea_prices_{pcat}: IEA prices, in US dollars per GJ

eel_{pg}: Electrical efficiency

$pcat$: Price category

$conGJMwh$: Conversion rate, GJ to MWh (3.6)

FIXED OPERATING COST

Fixed operating cost is estimated as follows:

$$\text{techpol\_fom}_{pg} = \frac{fom_{pg}}{lfc_{pg}} \cdot \frac{1000}{yhr} \cdot exr \quad [8]$$

where:

techpol_fom_{pg}: Fixed operation and maintenance cost in US dollars per MWh

fom_{pg}: Fixed operation and maintenance cost in Euro per KWy

VARIABLE OPERATING COST

Variable operating cost data are obtained from TECHPOL II database and are converted from Euro per MWh to US dollars per MWh as follows:

$$techpol\_vom_{pg} = vom_{pg} \cdot exr \quad [9]$$

where:

$techpol\_vom_{pg}$: Variable operation and maintenance cost in US dollars per MWh

vom_{pg}: Variable operation and maintenance cost in Euro per MWh

TOTAL PRODUCTION COST

Total production cost is estimated as the sum of the different cost components presented above, as follows:

$$tpc_{pg} = techpol\_kct_{pg} + techpol\_fom_{pg} + techpol\_vom_{pg} + techpol\_fct_{pg} \quad [10]$$

where:

tpc_{pg}: Total production in US dollars per MWh

BALANCING ROUTINE

In the *f_NRGsplit_BUPG.gms* file is codified the bottom-up representation of the power generation technologies. Here electricity sector is broken down by power generation technology. The formulation of the IO flows split program is summarized below.

The construction of the detailed bottom-up IO tables results from a balancing routine which respects as much as possible the initial IO tables, production shares and cost structures. The objective function of the balancing routine is given below and it aims at minimizing the sum of squares of deviations of production and market shares from the initial respective shares.

$$obj = weight\_production \cdot \sum_{fa,buprt} ERROR\_PRODUCTION\_STRUCTURE^2_{fa,buprt}$$ [11]

$$+weight\_marktet \cdot \sum_{buprt} ERROR\_MARKET\_SHARE^{\ 2}_{buprt} + weight\_materials \cdot \sum_{buprma,buprt} ERROR\_MATERIALS\_SHARE^{\ 2}_{buprma,buprt}$$

where:

$weight\_production$: Weight in the objective function of the cost structure constraint

$weight\_market$: Weight in the objective function of the market share constraint

$weight\_materials$: Weight in the objective function of the materials share constraint

$ERROR\_PRODUCTION\_STRUCTURE_{buprt}$: Deviation from initial production structure

$ERROR\_MARKET\_SHARE_{buprt}$: Deviation from initial market share

$ERROR\_MATERIALS\_SHARE_{buprma,buprt}$: Deviation from initial materials share

fa: Factors of production (labour, capital, fuels, materials)

MARKET SHARES AND PRODUCTION STRUCTURE

The deviations in market shares and power generation costs in the final IO tables as compared to the initial ones are formulated below. Deviations in market shares (in volume, GWh) for the different power generation technologies are given by the following equation:

$$ERROR\_MARKET\_SHARE_{buprt} = \log\left[1 + \left(\frac{QQ\_VOL_{buprt}}{\sum_{buprt1} QQ\_VOL_{buprt1}}\right)\right] - log(1 + market\_share\_target_{buprt})$$ [12]

where:

$buprt, buprt1$: Subset of power generation technologies

QQ_VOL_{buprt}: Electricity production by technology, in GWh

$market\_share\_target_{buprt}$: Market shares as derived from the energy balances

Four discrete production factors are considered: labour, capital, materials and fuels. The deviation in the production structure of the power generation sector in the final IO table as compared to the initial one is formulated as follows making distinction between different production factors:

For *fa*=materials:

$$ERROR\_PRODUCTION\_STRUCTURE_{fa,buprt} = weightma \cdot \left[\log\left(1 + \sum_{buprma} \frac{IOBU_{buprma,buprt}}{QQ\_VAL_{buprt}}\right) - \log(1 + production\_structue\_target_{fa,buprt}) \right]^2 \quad [13]$$

where:

$weightma$: Weight of materials cost structure constraint in objective function

$buprma$: Non-energy sectors

$IOBU_{buprma,buprt}$: Intermediate inputs of power generation and transmission and distribution

QQ_VAL_{buprt}: Electricity production by technology, in Euro

$production\_structure\_target_{fa,buprt}$: Production structure of power generation technologies.

For *fa*=capital:

$$ERROR\_PRODUCTION\_STRUCTURE_{fa,buprt} = weightka_{buprt} \cdot \left[\left(log\left(1 + \frac{KA_{buprt}}{QQ\_VAL_{buprt}}\right) - log(1 + production\_structure\_target_{fa,buprt})\right)\right]^2 \quad [14]$$

where:

$weightka$: Weight of capital cost structure constraint in objective function

KA_{buprt}: Operating surplus of power generation and transmission and distribution.

For *fa*=labour:

$$ERROR\_PRODUCTION\_STRUCTURE_{fa,buprt} = weightla \cdot \left[\log\left(1 + \frac{la_{buprt}}{QQ\_VAL_{buprt}}\right) - \log(1 + production\_structure\_target_{fa,buprt})\right]^2 \quad [15]$$

where:

$weightla$: Weight of labour cost structure constraint in objective function

la_{buprt}: Compensation of employees in power generation and transmission and distribution.

For *fa*=materials:

$$ERROR\_MATERIALS\_SHARE_{buprma,buprt} = \left|\log\left(1 + \frac{IOBU_{buprma,buprt}}{materialtotal_{buprt}}\right) - \log(1 + costructure\_materials_{buprma,buprt})\right| \quad [16]$$

where:

$materialtotal_{buprt}$: Total materials by technology

$costructure\_materials_{buprma,buprt}$: Cost structure of material by technology

RESOURCE CONSTRAINTS

Consistency of the derived bottom-up IO table with the initial one with regards to intermediate inputs, capital and labour is formulated as follows:

$$\sum_{buprele} buIO\_ini_{buprma,buprele} = \sum_{buprt} iobu_{buprma,buprt} + \sum_{buprele} iobu_{buprma,buprele} \quad [17]$$

for intermediate inputs and:

$$ka\_ini = \sum_{buprt} ka_{buprt} + \sum_{buprele} ka_{buprele} \quad [18]$$

$$la\_ini = \sum_{buprt} la_{buprt} + \sum_{buprele} la_{buprele} \quad [19]$$

for operating surplus and compensation of employees respectively where:

$bupr$: Power generation sectors in extended IO table

$buprele$: Electricity sector

$buIO\_ini_{bupr,buprele}$: Initial bottom-up IO table

ka_ini: Operating surplus of power generation and transmission and distribution in initial IO table

la_ini: Compensation of employees in power generation and transmission and distribution in initial IO table.

ELECTRICITY GENERATION BY TECHNOLOGY

Power generation volumes are formulated in the following equation:

$$\sum_{buprt} QQ\_vol_{buprt} = \sum_{ptec} heatele\_out_{ptec} \quad [20]$$

where:

$heatele\_out_{ptec}$: Production of heat and electricity by technology in GWh

$ptec$: Power generation technologies represented by the model

TRANSMISSION AND DISTRIBUTION

Transmission and distribution IO values are calculated as residuals. Transmission and distribution intermediate inputs are formulated as follows by making use of the initial IO table:

$$\sum_{buprele} iobu_{buprma,buprele} = \sum_{buprele} buIO\_ini_{buprma,buprele} - \sum_{buprt\_ma} iobu_{buprma,buprt\_ma} \quad [21]$$

where:

$buprt\_ma$: Subset of power generation technologies that use materials.

For operating surplus and compensation of employees in the transmission and distribution sector the following equations are employed:

$$\sum_{buprele} ka_{buprele} = 1 = \mathrm{sh} \cdot ka\_ini \qquad [22]$$

for operating surplus and:

$$\sum_{buprele} la_{buprele} = 1 = \mathrm{sh} \cdot la\_ini \qquad [23]$$

for compensation of employees accordingly.

EXTENDED IO TABLES

Table 5-Table 7 depict by way of example the split of the German energy sector using the bottom-up engineering information and the assumptions related to the mapping of engineering variables and IO macroeconomic variables. The tables provide 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. When trying to match engineering data with macroeconomic data several incompatibilities occur (for instance the shares suggested by the engineering data do not match the macroeconomic information as they result in the transmission and distribution sector having a negative value in capital (Table 6)). Similar incompatibilities occur for all GTAP countries although they range depending on the accuracy of the statistical IO and engineering data and the appropriateness on the assumptions made for the correspondence between the datasets.

Table 5: German IO table, in million $ 2011

	Coal	Oil	Gas	Agriculture	Materials	Electricity	Final demand	Total demand
Coal	4	3005	1	0	867	13432	303	17612
Oil	12	47036	2	157	116245	4924	63201	231578
Gas	0	333	87	1	12125	7175	7824	27545
Agriculture	40	5	3	5258	74061	11	32658	112036
Materials	7026	82609	1606	30217	2954130	29439	4682968	7787996
Electricity	373	2240	79	9	68674	5588	33032	109995
Capital	6511	3130	1100	13726	1209615	19218		
Labour	4131	1368	713	18257	1301884	13541		
Taxes	-6827	55884	870	10152	748866	11122		
Imports	6343	35969	23083	34258	1301528	5546		
Total supply	17612	231578	27545	112036	7787996	109995		

Table 6: German energy sector disaggregation based on bottom-up data

	Coal	Oil	Gas	Agriculture	Materials	T&D	Coal fired	Gas fired	Oil fired	Nuclear	Biomass	Hydro	Wind	PV	Waste	Geothermal	TidalWave	Solar thermal	Coal fired with CCS	Gas fired with CCS	Final demand	Total demand
Coal	4	3005	1	0	867	3843	9589	0	0	0	0	0	0	0	0	0	0	0	0	0	303	17612
Oil	12	47036	2	157	116245	3703	0	0	1221	0	0	0	0	0	0	0	0	0	0	0	63201	231578
Gas	0	333	87	1	12125	759	0	6415	0	0	0	0	0	0	0	0	0	0	0	0	7824	27545
Agriculture	40	5	3	5258	74061	11	0	0	0	0		0	0	0		0	0	0		0	32658	112036
Materials	7026	82609	1606	30217	2954130	27823	708	227	28	424	171	0	0	0	58	0	0	0	0	0	4682968	7787996
T&D	373	2240	79	9	68674	5588	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33032	109995
Coal fired	0	0	0	0	0	18782	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18782
Gas fired	0	0	0	0	0	8127	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8127
Oil fired	0	0	0	0	0	1384	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1384
Nuclear	0	0	0	0	0	7276	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7276
Biomass	0	0	0	0	0	3177	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3177
Hydro	0	0	0	0	0	1568	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1568
Wind	0	0	0	0	0	5601	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5601
PV	0	0	0	0	0	6383	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6383
Waste	0	0	0	0	0	804	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	804
Geothermal	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
TidalWave	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solar thermal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal fired with CCS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gas fired with CCS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Capital	6511	3130	1100	13726	1209615	-8979	7058	1181	98	5533	2432	1240	4392	5712	551	1	0	0	0	0		
Labour	4131	1368	713	18257	1301884	7476	1427	305	38	1320	573	328	1209	671	195	0	0	0	0	0		
Taxes	-6827	55884	870	10152	748866	11122	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Imports	6343	35969	23083	34258	1301528	5546	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Total supply	17612	231578	27545	112036	7787996	109995	18782	8127	1384	7276	3177	1568	5601	6383	804	1	0	0	0	0		

Application of the above mentioned calibration technique in the German matrix resulted in Table 7 where the macroeconomic constraints are satisfied at the expense of markets shares and technology cost structures (in particular capital).

Table 7: The balanced German IO table, in million $2011

	Coal	Oil	Gas	Agriculture	Materials	T&D	Coal fired	Gas fired	Oil fired	Nuclear	Biomass	Hydro	Wind	PV	Waste	Geothermal	TidalWave	Solar thermal	Coal fired with CCS	Gas fired with CCS	Final demand	Total demand
Coal	4	3005	1	0	867	3843	9589	0	0	0	0	0	0	0	0	0	0	0	0	0	303	17612
Oil	12	47036	2	157	116245	3700	0	0	1221	3	0	0	0	0	0	0	0	0	0	0	63201	231578
Gas	0	333	87	1	12125	758	0	6417	0	0	0	0	0	0	0	0	0	0	0	0	7824	27545
Agriculture	40	5	3	5258	74061	7	0	0	0	0	3	0	0	0	0	0	0	0	0	0	32658	112036
Materials	7026	82609	1606	30217	2954130	27884	708	227	28	421	171	0	0	0	0	0	0	0	0	0	4682968	7787996
T&D	373	2240	79	9	68674	5588	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33032	109995
Coal fired	0	0	0	0	0	15553	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15553
Gas fired	0	0	0	0	0	8038	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8038
Oil fired	0	0	0	0	0	1384	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1384
Nuclear	0	0	0	0	0	5292	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5292
Biomass	0	0	0	0	0	2797	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2797
Hydro	0	0	0	0	0	1468	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1468
Wind	0	0	0	0	0	4351	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4351
PV	0	0	0	0	0	4269	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4269
Waste	0	0	0	0	0	726	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	726
Geothermal	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
TidalWave	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solar thermal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal fired with CCS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gas fired with CCS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Capital	6511	3130	1100	13726	1209615	192	3829	1090	97	3549	2049	1140	3142	3597	531	1	0	0	0	0		
Labour	4131	1368	713	18257	1301884	7476	1427	305	38	1320	573	328	1209	671	195	0	0	0	0	0		
Taxes	-6827	55884	870	10152	748866	11122	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Imports	6343	35969	23083	34258	1301528	5546	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Total supply	17612	231578	27545	112036	7787996	109995	15553	8038	1384	5292	2797	1468	4351	4269	726	1	0	0	0	0		

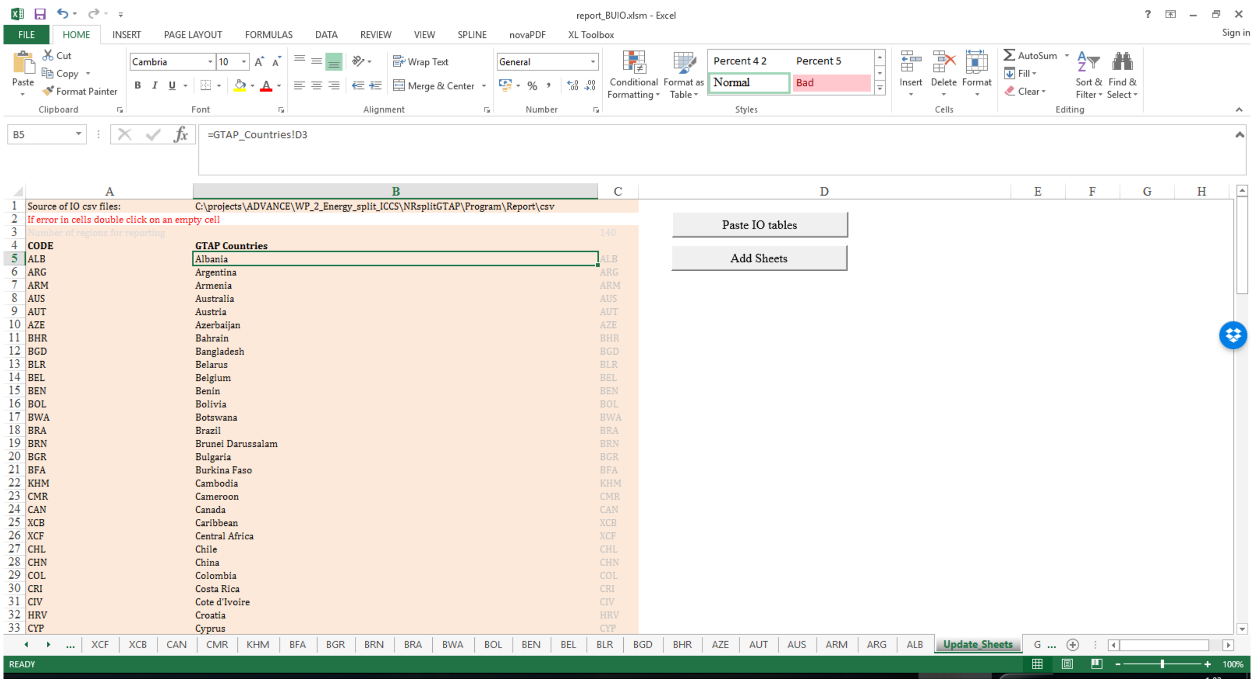
REPORTING THE EXTENDED IO TABLES

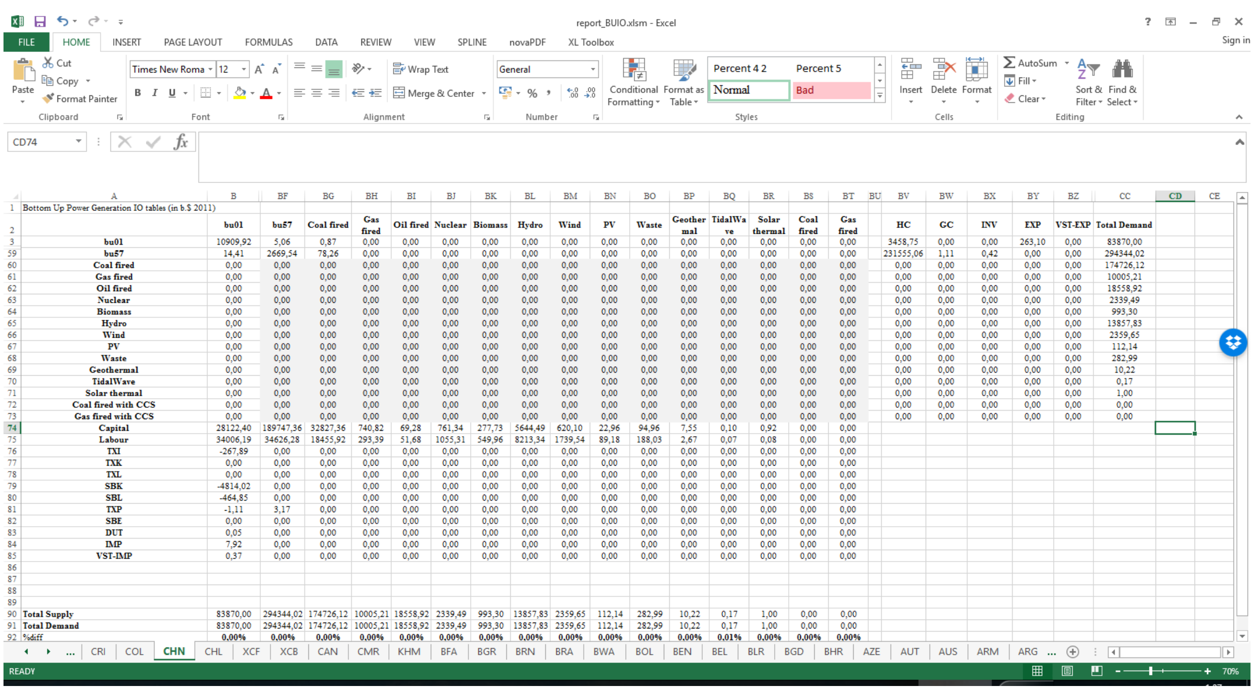
The final section of the energy split routine reports the extended IO tables both in *csv* and in excel format.

Once the balancing routine has converged to the extended IO, all results are exported in *csv* files. The *csv* files are stored in the *ADVANCE\WP_2_Energy_split\NRsplitGTAP\Program\Report\csv* folder. These *csv* files are collected by a macro enabled excel file that prepares the formatted presentation of the input output tables. The name of the excel file is r*eport_BUIO.xlsm* and the file is stored in *ADVANCE \WP_2_Energy_split\NRsplitGTAP\Program\Report folder*.

In the sheet *Update_Sheets* of the r*eport_BUIO.xlsm* file the user can automatically copy and paste all IO tables that are stored in *csv* to individual sheets of the excel file. To do so the user needs to identify the locations of the IO *csv* files in the machine, this is done in cell B1 (see Figure 5 for an example). Once the correct path of *csv* files is given the button *Paste IO tables* should be pressed so as to perform the collection of the files. As this procedure involves the use of macros the appropriate changes in macro security settings should be made in order to allow the use of macros.

Figure 5: The extended IO tables in excel file





CALIBRATION OF ENERGY VOLUMES, TAXES & SUBSIDIES

The GTAP-IEA dataset has been used in order to calibrate the energy volumes of the GTAP database. GTAP does not have an explicit representation of energy taxes and subsidies.The precise representation of taxation in CGE models is important since together with the production costs they determine the relative price system that coordinates agent's actions. The GTAP database identifies three main categories of taxes/subsidies: i) factor taxes, ii) trade taxes and iii) taxes on products. The representation of energy prices, subsidies and taxes in the GTAP database has been improved for a number of countries using the output of WP3, Task 3.2 "Energy prices and subsidies". In particular the tax and subsidy rates of the IEA database have been used to calculate the values of taxes and subsidies imposed on energy. These transactions where then subtracted from the row of the IO table corresponding to taxes & products of the GTAP database.

The tax and subsidy rates suggested by the database of Task 3.2 resulted in plausible revenues/expenditures for the public budget of each country (Table 8). The energy prices and associated tax system has been included in the GEM-E3 model ensuring consistency with the overall General Equilibrium framework.

Table 8: Energy taxes and subsidies

year: 2015	billion US$2005/yr			% GDP	
	GDP|MER	Taxes|Final Energy	Subsidies	Taxes|Final Energy	Subsidies
EU28	14176	672	18	4,7%	0,1%
USA	14880	118	3	0,8%	0,0%
Japan	4666	115	0	2,5%	0,0%
Canada	1308	19	2	1,4%	0,2%
Brazil	1186	20	0	1,7%	0,0%
China	5437	129	9	2,4%	0,2%
India	1669	42	18	2,5%	1,1%
Korea	1221	40	0	3,3%	0,0%
Indonesia	501	2	16	0,5%	3,1%
Mexico	1088	11	3	1,1%	0,3%
Argentina	344	8	3	2,4%	1,0%
Turkey	659	24	0	3,6%	0,1%
S.Arabia	577	0	105	0,0%	18,2%
Oceania	1033	12	1	1,1%	0,1%
Russia	1059	44	48	4,2%	4,6%
R. Energy Producers	1607	5	128	0,3%	8,0%
South Africa	323	6	0	2,0%	0,0%
Rest of Europe	1037	25	3	2,4%	0,3%
Rest of the World	4260	63	55	1,5%	1,3%
World	57032	1356	413	2,4%	0,7%

COMPARING ELECTRICITY SECTOR DISAGGREGATION APPROACH TO THE GTAP-POWER APPROACH

In a recent paper Peters (2015) documents the methodology to create the GTAP-Power database, an electricity-detailed CGE database with transmission and distribution and several generating technologies. The GTAP-Power database extends the GTAP v.9 database. The methodology leverages available economic and technological data along with assumptions regarding the structure of the electricity sector. Below are summarized the main data and methodology employed for the development of the GTAP-Power database and a brief comparison with the disaggregation and modelling of the power generation sector discussed above.

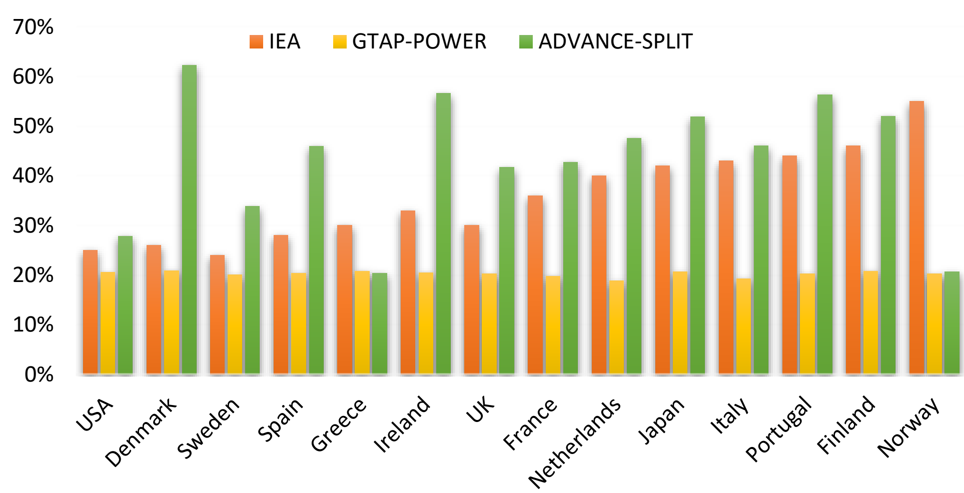
GTAP-Power makes use of the following data: i) electricity production (in GWh) by fuel source, ii) total value of inputs (in base year USD) to an aggregate electricity sector for each source (i.e., domestic and import) for base years 2004, 2007 and 2011 and iii) levelized capital (i.e. annualized cost per GWh), operating and maintenance, fuel and effective tax costs of electricity for selected generating technologies and regions. Power generation technologies are split into base and peak load power. Disaggregation is made into: transmission and distribution, seven base load technologies (Nuclear, Coal, Gas, Hydro, Oil, Wind and Other) and four peak load technologies (Gas, Oil, Hydro, and Solar).

The splitting methodology in GTAP-Power develops in two-stages. The first one completes the splitting of power generation between base and peak load for the generating technologies then in the second stage the full matrix is filled given the split undertaken in the first stage. The base-peak load split stage minimizes the total O&M and fuel costs of base load production subject to GWh clearing constraints and the assumption that base load must account for at least 85% of total GWh produced. In the second stage the disaggregated matrix is balanced with the employment of a Share-Preserving Cross-Entropy (SPCE) method, where constraints are imposed to maintain an assumed allocation of value to transmission and distribution and ensure consistency with the GTAP database. In this stage are treated deviations between estimated and targeted costs and large data disparities. Constraints are also imposed so as to ensure sufficient and proportional allocation of fuels into their associated technologies (e.g., total fuel costs of coal-based generation are greater or equal to the total coal costs to electricity in the GTAP database).

With regards to O&M costs GTAP v.9 database has 58 costs which fall broadly under the umbrella of O&M costs including five labor classes and various agricultural, machinery, chemical, and transportation sectors. While not much data exists regarding how these sub-sectors enter either transmission and distribution or specific generating technologies, some basic assumptions are made regarding their shares. The shares are treated as probabilities that an input cost enters the new sectors. GTAP database includes five sectors which correspond to fuel costs: coal, gas pipeline, distributed gas, oil and petroleum and coal products. These are allocated using basic assumptions and conditionals when those assumptions break down. Regarding capital costs a similar formulation found in McDougall (1999) is employed. Total own-use costs in the electricity sector in each region come directly from own-use in the original GTAP database. Tax costs are assumed fixed and are assigned by the value implied by the levelized tax from the data and total GWh production data.

The demand-side share allocation for each electricity sector is assumed identical to the mix implied by the sum of domestic production and the net imports. The disaggregation of the demand-side assumes all users demand identical shares of transmission and distribution and of each generating technologies.

Figure 6: Share of transmission and distribution costs in total power generation costs (2011)

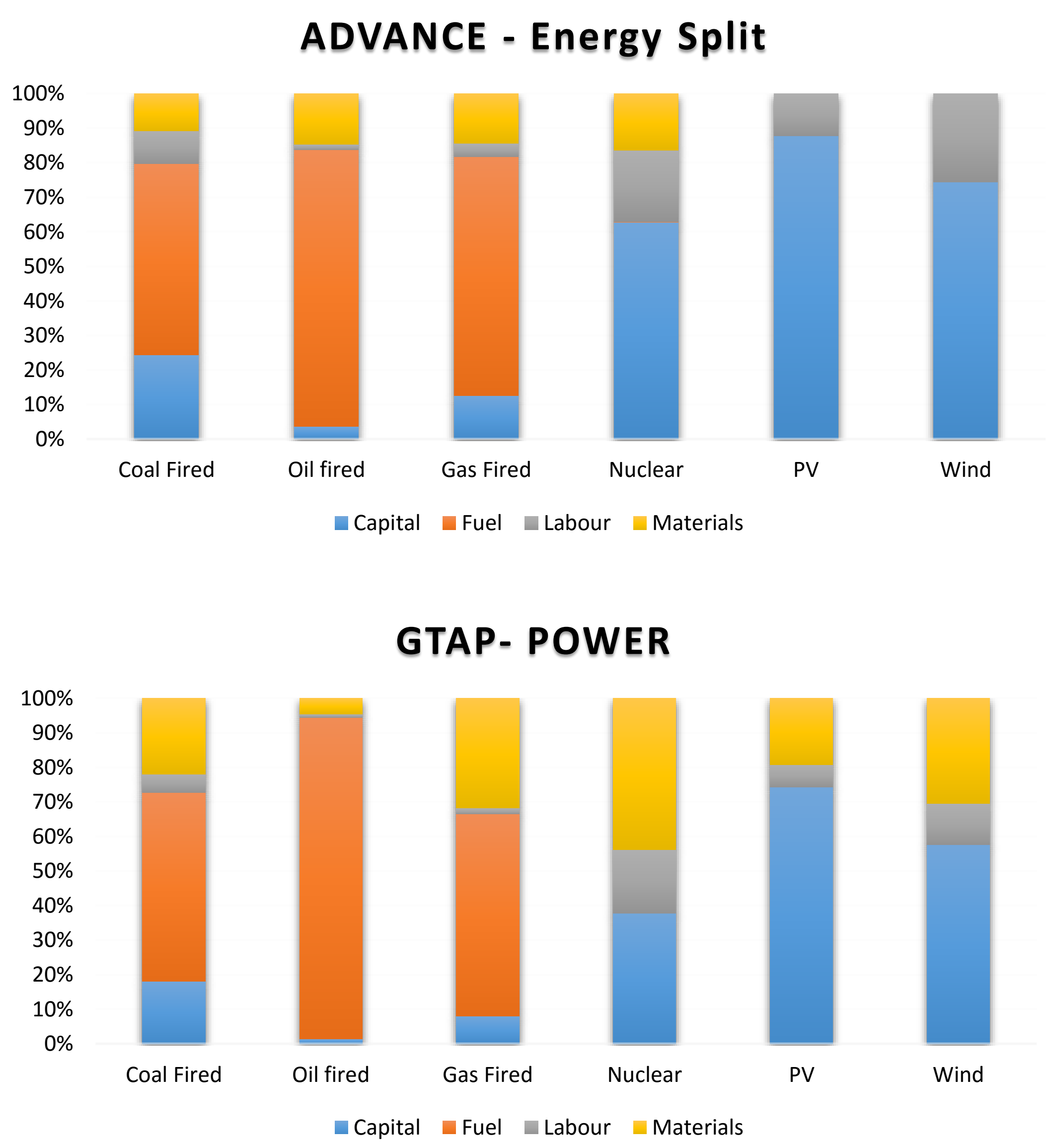


Source: Authors calculations

Figure 6 presents the results for selected countries of the GTAP-Power and ADVANCE – Energy split regarding the computation of the costs of transmission and distribution of electricity and compares with IEA statistics. The GTAP–power results an almost uniform share of 21% across countries, which consistently underestimates the reported costs by IEA, capturing however a correct order of magnitude. In the ADVANCE–Energy split routine the T&D costs are calculated as a residual (i.e. at first the costs of all power generation technologies are calculated and then subtracted from the "initial" GTAP power generation sector). For the majority of the countries the results are close to the reported statistics by IEA apart from few exceptions (in the graph these are Denmark, Spain and Ireland).

In presenting the computed cost structures by each approach the base load technologies from GTAP have been selected. Figure 7 presents the representative costs structures as resulted by each approach. The results are comparable apart from the RES technologies (Wind and PV) where by assumption in the ADVANCE-Energy split routine materials have been excluded from the propduction function of PV and Wind.

Figure 7: A comparison of power generation cost structures (universal technologies)



The output of the two approaches is comparable. Differences can be attributed to different balacing routines adopted (the GTAP-Power adopts a distance minimization approach whereas the ADVANCE-Energy split uses a weighted objective function) but also due to different engineering datasets.

LINKING TOP-DOWN AND BOTTOM-UP MODULES

Several approaches have been proposed and used for the modelling of the power generation sector. These vary from “top-down” macroeconomic modelling approaches, that incorporate in a simplified manner the power generation sector within a larger macroeconomic system, to ”bottom-up” modules that model in detail the power generation sector, with limited though representation of its links with the wider economic system. Top-down models emphasize on the economy-wide while bottom-up models focus on sectorial and technological details. The traditional top-down macroeconomic approach might lead to simplified representation of the power generation failing to capture adequately the substitutions possibilities between the different power generation technologies. This level of information is available in bottom-up models which however fail to capture any macroeconomic interactions. Top-down models perform well in terms of microeconomic realism and of macroeconomic feedbacks if they are general equilibrium models. Nevertheless, they lack technological explicitness, making them ineffective for assessing the full range of policies that policy makers may wish to consider (Andersen and Termansen, 2013).

Conventional bottom-up models do well in their ability to investigate the impacts of energy policy on the technology portfolio, in order to identify low-cost opportunities or design technology-based taxes, subsidies or standards. On the other hand the comparative strength of the top-down models lies on their ability to assess the macroeconomic costs of a policy shock and its economy-wide feedbacks on prices, commodity and factor substitution, income and economic welfare. The analytical contributions of bottom-up and top-down approaches are in large complementary, however their results tend to diverge, with top-down models typically indicating larger macroeconomic costs of policies assessed (National Academy of Sciences, 1991; Grubb et al., 1993; Wilson and Swisher, 1993; IPCC, 1995, 2001). The divergence in results has been associated with the technological optimism of bottom-up models. The literature has indicated that it remains unclear how, for a given degree of technological optimism, the behavior of top-down models will respond to the inclusion of more realistic specifications of individual energy technologies (Wing, 2006).

Top-down models typically represent energy production technologies through aggregated production functions. The advantage of this approach is that it enables the inclusion of energy supply and demand decisions within an internally consistent macroeconomic framework.

Nevertheless these approaches lack the technological, spatial and temporal resolution. On the other hand, bottom-up models provide a technology-rich and of high resolution representation of the energy system but they fail to include interactions of the sector with the broader economic system due to their partial equilibrium nature. Hence bottom-up models fail to adequately incorporate macro-economic determinants of energy demand and supply and they cannot assess policies in terms of their social cost like impact on GDP, consumption etc. (see Hourcade et al., 2006).

Traditional modelling approaches have been able to generate adequate and reliable model-based approximations of real-world energy production for systems characterized predominantly by fossil-based energy sources and technologies. Macro-economic top-down models have been widely used as analytical tools for the investigation of the impacts of energy and climate policy in terms of technological pathways, environmental impacts (i.e., greenhouse gas emission reduction potentials) and their social costs and benefits. While the macroeconomic models have been useful tools for the derivation of policy recommendations, they lack of the appropriate level of detail so as to adequately capture substitutions possibilities between intermittent renewable energy sources and thermal technologies. Intermittent resources (wind, solar) require detailed temporal and spatial analyses, as well as, the study of operational implications such as the need for additional reserve requirements, storage and transmission capacity (see Tapia-Ahumada et al., 2015).

In the standard CGE models energy is modelled through aggregate production functions. This has subjected CGE modelling to criticism due to the simplified representation of the energy systems, which limits the ability of the models to capture core characteristics of the sector, rendering thus weak the simulation results associated with energy policies and technology dynamics. Since the hybrid CGE model of Manne (1977) applied energy policy analysis has been studying the development of a modelling framework that could encompass the multi-market equilibrium of top-down models with an engineering consistent representation of power producing technologies.

"Hybrid" modelling approaches aim at combining the technological explicitness of bottom-up models with the economic richness of top-down models. Hybrid models bridge the bottom-up and top-down divide by integrating the detailed representation of energy technologies found in bottom-up models into CGE models' equilibrium structure (Böhringer, 1998; Böhringer et al., 2003; Frei et al., 2003; Kumbaroglu and Madlener, 2003; McFarland et al., 2004). However their development is faced with several challenges. The key challenge in introducing the detailed description of the technology frontier into a general equilibrium framework, is the so-called ''flip flop'' problem, whereby small changes in technologies' unit costs give rise to implausibly large changes in their activity levels and market shares technologies (Wing, 2006). Such behavior is not desirable in static models in which discrete technologies are perfect substitutes, and in forward-looking models with an activity-analysis representation of production in which producers' inter-temporal adjustments of technology-specific capital stocks are fundamentally linked to their intra-temporal capacity utilization decisions. Addressing of this issue requires careful specification of the competition among technologies, and the adjustment process of technology-specific capital.

A further challenge pointed in the literature with regards to hybrid models is associated with the calibration of the bottom-up top-down structure, which necessitates adequate addressing of reconciling incommensurate data on the electricity sector's demands for inputs, statistics on the distribution of generation by technology, and engineering estimates of the latter's unit input requirements (Wing, 2006).

Additional challenges to constructing a hybrid model stem from the need to represent the static (intra-temporal) and dynamic (inter-temporal) aspects of technology substitution. The homogeneity of electric power as a commodity belies the significant variation in the characteristics of the technologies employed in its generation. The merit order of a base load coal or nuclear unit, a gas-fired peaking plant or a wind turbine differ substantially, reflecting these technologies' disparate availability factors and fuel and capital costs per kWh. Moreover, different technologies will typically produce output for different segments of the load duration curve implying that multiple types of generation with different marginal costs are simultaneously dispatched (Wing, 2006). Thus production structure needs to be modelled in a way that respects the balance between the homogeneity of electric power and imperfect substitutability with respect to different segments of the load-duration curve. By comparison, the challenge of representing the inter-temporal dimension of technology substitution is greater, as it necessitates modelling the process by which producers adjust stocks of technology-specific capital. This is usually achieved through the capacity adjustment specification found in dynamic general equilibrium simulations based on the Kuhn–Tucker conditions of the standard Hayashi–Summers profit maximization problem of a forward-looking producer (e.g., Frei et al., 2003). Nevertheless the computational implementation of such models remains challenging. Data on investment in energy supply technologies is in most cases missing rendering thus more preferable approaches of a balanced growth path calibration which force technologies' market shares to remain constant over the baseline trajectories of the model.

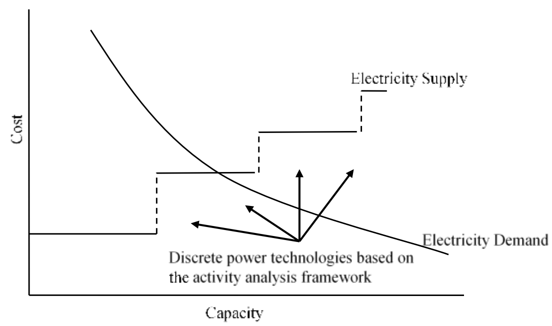
The literature offers several top-down bottom-up linking examples (see for instance Messner and Schrattenholzer, 2000; Muller, 2000; Kumbaroglu and Madlener, 2001; Hourcade et al., 2006; Remme and Blesl, 2006; Schäfer and Jacoby, 2006; Jochem et al., 2007 and Catenazzi, 2009) that develop mainly along a “soft-” or “hard-” linking approaches. Böhringer and Rutherford (2009) distinguish between different cases that include: i) coupling of existing large-scale bottom-up and top-down models, ii) combining one model type with a "reduced form" representation of the other and iii) combining bottom-up and top-down characteristics directly through the specification of market equilibrium models as mixed complementarity problems (further elaborated in Cottle et al., 1992 and Rutherford, 1995). Each approach comes with advantages and disadvantages. When soft-linking (case i) across bottom-up and top-down models the differences in model setup and accounting methods could potentially cause convergence issues in aligning them through iterative procedures. The reduced form approach (case ii, hard-linking) may simplify the representation of one model significantly. Last the integrated mixed complimentary approach (case iii) may also suffer from complexity and dimensionality issues limiting thus significantly its practical implementation.

Soft-linking attempts to align top-down and bottom-up models in order to keep their respective strengths. Soft-linking signifies that the macroeconomic top-down model and the energy system bottom-up models are linking through an iterative process, where convergence of central parameters is satisfied-e.g. price and quantity parameters (Kumbaroglu & Madlener, 2003). In soft-linked models the macroeconomic and the energy system model operate together in an iterative process until convergence in central parameters is achieved. This approach can take advantage of benefits present in both models (for instance CGE model addresses economic behavior and general equilibrium effects while the energy system model better captures changes in energy carriers and the competition for limited energy resources by a detailed description of available technology options end energy potentials for each energy carrier). On the negative side, it might be difficult to achieve consistency between the models when the differences in structure and methodology can be significant (Böhringer and Rutherford, 2009).

In hard-linking, the related characteristics of bottom-up and top-down models are highly integrated and this may often imply a simplified description of either model in contrast to soft-linking in which also relatively large-scale models are kept intact (e.g., Bauer et al, 2007; Böhringer and Rutherford, 2009). Hard-linking approaches imply that the properties of the bottom-up and top-down models are integrated into a single model that is solved in a simultaneous optimization. This often develops on a simplified description of either bottom-up or top-down aspect in the integrated the model.

The hard-linking approach has been further subject to criticism due to the treatment of investment decisions as investment is either exogenously allocated to electricity technologies or decided at the level of the aggregate electricity sector and then allocated to each technology using a logit function. The formulation of investment decisions in this way allows for multiple technologies with different costs to coexist, although it does not adequately capture the investment behavior of the electricity sector where each sector should decide the level of investment as a function of its profit and then this investment demand should be translated to demand for investment products produced by other sectors. Moreover the non-smooth representation of power supply results in sharp shifts in the technology mix of electricity production implying unrealistic switching between technologies (Figure 8).

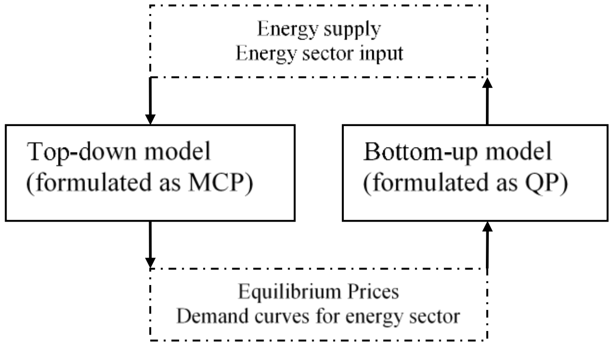
Figure 8: "Knife edge" switching between technologies



In the mixed complementarity problem, the modelling innovation relies on the development of powerful solving algorithms in the 1990's (Dirkse and Ferris, 1995) and their implementation in GAMS. Mathiesen (1985) demonstrates how to formulate a general economic equilibrium for an Arrow-Debreu economy in a complementarity format. Böhringer and Rutherford (2009) then proceed to show that "*complementarity is a feature of economic equilibrium rather than an equilibrium condition per se*". The complementarity format allows to cast an equilibrium in the form of weak inequalities, establishing a logical connection between prices and market clearing conditions (Miess et al., 2014). The properties of this format then make it possible to directly integrate bottom-up activity analysis into a general equilibrium top-down representation of the economy.

Other advantages of the mixed complementarity format are that the so-called integrability conditions (Pressman, 1970 and Takayama and Judge, 1971) inherent to economic models cast as optimisation problems can be relaxed. In Böhringer & 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 as illustrated in Figure 9.

Figure 9*:* Iterative decomposition algorithm suggested by Böhringer & Rutherford (2006)



The literature documents several methodologies that integrate bottom-up and top-down features through the specification of market equilibrium models as mixed complementarity problems (see Cottle et al., 1992 and Rutherford, 1995). A characteristic example of this approach can be found in Böhringer (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 CGE model. This 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 used in the model are replaced by a set of discrete Leontief technologies (fixed input/output vector). In a similar manner McFarland et al. (2002) suggest a more flexible format through a CES representation of energy technologies. In this approach the energy sector is split using engineering bottom-up data and consequently the smooth production function of the model is calibrated on these data. In this 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 CES production function. Each technology produces electricity through a CES 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 development of hybrid models addresses the need for more thorough representation of the electricity sector investment decision. Nevertheless, the modelling literature offers limited efforts on the development of bottom-up top-down models. This is associated with difficulties arising from the integration of macroeconomic and engineering data in a consistent way. Next section presents the mathematical formulation of:

(i) The standard aggregate representation of power sector through a CES function

(ii) A discrete representation of power generation using extended IO tables and Weibull function

(iii) A hard link between a power generation model and a detailed CGE model

TYPICAL POWER SECTOR REPRESENTATION VIA A CES FUNCTION

The power producing sector is modelled by a representative firm that maximises its profits Π, within a perfect competition market regime, subject to a constant elasticity of substitution (CES[4]) production function.

$$\max \Pi_i = P_i \cdot Q_i - PK_i \cdot K_i + PL_i \cdot L_i + PFUEL_i \cdot FUEL_i \quad [24]$$

$$s.t\ \ Q_i = \bar{Q} \cdot \left(d_i^k \cdot \left(\frac{K}{\bar{\bar{K}}}\right)^{\rho} + d_i^l \cdot \left(\frac{L}{\bar{\bar{L}}}\right)^{\rho} + d_i^{fuel} \cdot \left(\frac{FUEL}{\overline{FUEL}}\right)^{\rho} \right)^{\frac{1}{\rho}} \quad [25]$$

where:

Q: Production in volume

$\bar{Q}$: Production in volume (base year)

K: Production factor-Capital

L: Production factor-Labour

d: Share parameter

ρ: Elasticity ($\rho = \frac{\sigma-1}{\sigma}$)

σ: Elasticity of substitution

i: Activity

The solution to the above optimization problem is the following derived demand for capital and labour:

$$K_i = \bar{K}_\iota \cdot \frac{Q_i}{\bar{Q}_\iota} \cdot \left(\frac{\overline{PK}_\iota \cdot P_i}{\bar{P}_\iota \cdot PK_i}\right)^{\sigma} \quad [26]$$

[4] The calibrated share form as used in Rutherford (2009) is adopted.

$$L_i = \overline{L_\iota} \cdot \frac{Q_i}{\overline{Q_\iota}} \cdot \left(\frac{\overline{PL_\iota} \cdot P_i}{\overline{P_\iota} \cdot PL_i}\right)^\sigma \quad [27]$$

$$Fuel_i = \overline{Fuel_\iota} \cdot \frac{Q_i}{\overline{Q_\iota}} \cdot \left(\frac{\overline{PFuel_\iota} \cdot P_i}{\overline{P_\iota} \cdot PFuel_i}\right)^\sigma \quad [28]$$

DISCRETE POWER SECTOR REPRESENTATION

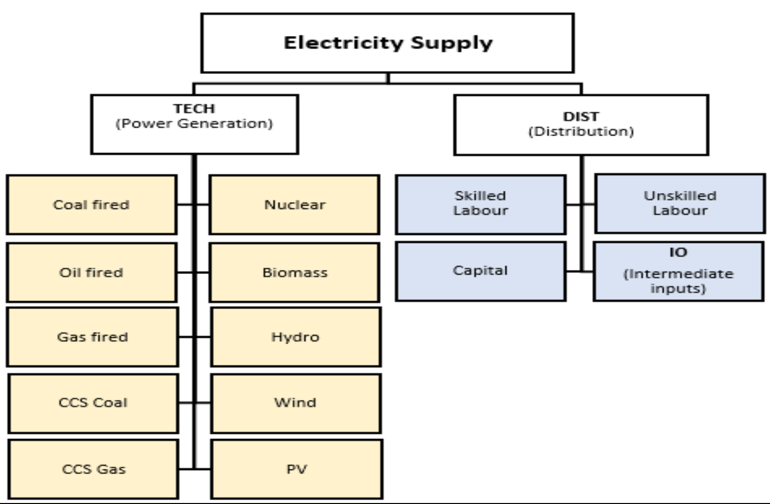
The nesting scheme for the electricity supply sector is presented in Figure 10. This sector regards the electricity generation and distribution.

Two options can be adopted in calculating the power mix:

i) Endogenous least cost calculation based on the firms optimisation

ii) Calibration to exogenous power mix shares (in this option it is the share parameters of the production function that are calibrated to the exogenous market shares). Data on market shares can be obtained from energy balance statistics and energy focused models with detailed representation of the different power generation technologies. 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. Hence in the model calibration provision should be made so as to introduce artificially small shares even for the non-existing technologies in order to allow for the possibility of their penetration in the future.

Figure 10: Nesting of electricity supply sector



The nesting scheme develops as follows:

1st level:	XD is split into power producing technologies bundle (*TECH*) and transmission and distribution bundle (*DIST*)

$A\_XD = \mathbf{LEONTIEF}(A\_TECH, A\_DIST)$

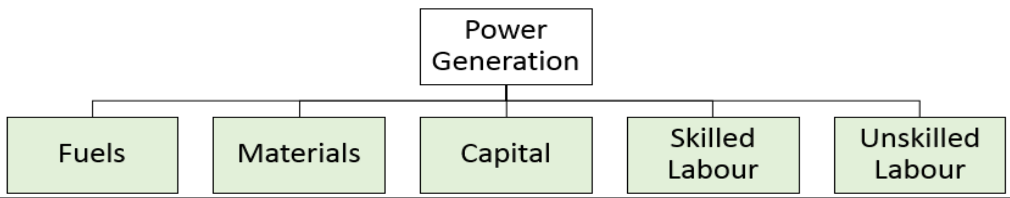
2nd level:	TECH is split into power generation technologies in the same nest (*IO*) DIST is spit into capital, skilled and unskilled labour and intermediate input materials (*IO*)

$A\_TECH = \mathbf{LEONTIEF}(A\_XD_{prtec})$ or $A\_TECH = \mathbf{WEIBULL}(A\_XD_{prtec})$ with exogenous or endogenous power mix shares, respectively

$A\_DIST = \mathbf{LEONTIEF}(A\_KAV, A\_LAV\_SKLD, A\_LAV\_UNSKLD, A\_IO_{pr})$

The nesting scheme for power producing technologies is presented in Figure 11.

Figure 11: Nesting of the power producing technologies



Power generation technologies exhibit a one level production function that includes capital, skilled and unskilled labour, materials and fuels.

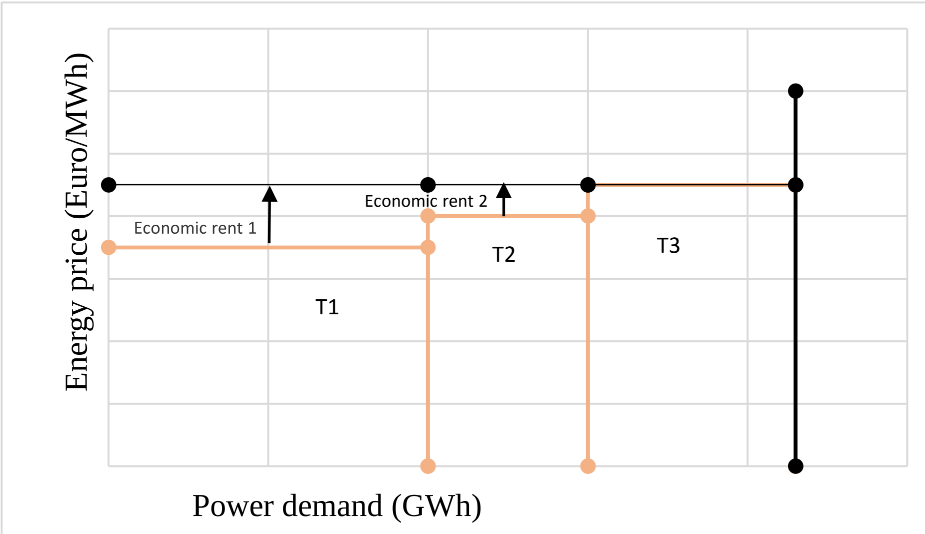
$A\_XD = \mathbf{LEONTIEF}(A\_KAV, A\_LAV\_SKLD, A\_LAV\_UNSKLD, A\_IO)$

SOFT LINK TOP - DOWN BOTTOM - UP

Modelling of the power generation technologies is subject to non-linearities (like fuel cost that reflects changes in marginal cost due to changes in fuel inputs used). In a similar manner non-linear relationships apply to RES technologies that consider the cost of additional installations (for instance construction of sites firs undertaken in places with more favorable conditions). In modelling the power generation sector the following assumptions can apply: i) In the short run demand is covered by the available power generation technologies, ii) System marginal price is set by the marginal price of the most expensive technology, iii) Technologies that are used in full capacity (in each time segment) earn an economic rent equal to the difference between their marginal cost and the market price, iv) Technologies with marginal cost higher than the system marginal price do not produce.

Competition between different technologies in power production can be illustrated as shown in Figure 12 (for simplicity technologies are assumed to have fixed marginal cost). Different technologies (T1, T2, T3) compete for a share in the power generation market. The technology with the lowest Marginal Cost (T1) can fulfil demand based on its capacity. The same applies for the next most expensive technology (T2). Last the most expensive technology (T3) covers the amount of demand that is left unaddressed from the other two technologies.

Figure 12: Competitive power market



Investments in new power plants are determined by changes in demand, technological improvements and unit decommissioning. Investment decisions take into account both the cost of unit production and the annualized fixed cost of investment. Modelling of the power generation sector includes constraints associated with the satisfaction of demand in different demand zones and points in time and constraints associated with intermittent energy sources (such as wind and hydro).

The following subsections provide a brief discussion on the representation of the power generation sector through non-linear and mixed-complementarity formulation.

POWER SECTOR OPTIMIZATION PROBLEM

In the power supply sector maximization of social utility can be written as a problem of minimizing the overall cost of production and investment, where the objective function can be formulated as follows:

$$Min\ OC$$
$$s.t.$$

$$OC = \sum_{tec,vtime,dem,runtime} \left(\frac{1}{1+\delta}\right)^{runtime-ts} \cdot NLFUELC_{tec,vtime,dem,runtime} + \sum_{tec,vtime,dem,runtime} \left(\frac{1}{1+\delta}\right)^{runtime-ts} \cdot vomc_{tec,vtime,dem,runtime} + \sum_{tec,vtime} \sum_{runtime \geq vtime} \left(\frac{1}{1+\delta}\right)^{runtime-ts} \cdot (FC_{tec,vtime} - invnl_{tec,vtime} \cdot \log(1 - \frac{KAVCT_{tec,vtime}}{pot_{tec,vtime}})) + \sum_{tec,vtime} \sum_{rtime \geq vtime} \left(\frac{1}{1+\delta}\right)^{runtime-ts} \cdot pot_{tec,vtime} \cdot invnl_{tec,vtime} \cdot (\frac{KAVCT_{tec,vtime}}{pot_{tec,vtime}} + \log(1 - \frac{KAVCT_{tec,vtime}}{pot_{tec,vtime}})) \quad [29]$$

$$FUEL_{tec,vtime,dem,runtime} = heatrate_{tec,vtime,dem,runtime} \cdot dur_{dem} \cdot GEN_{tec,vtime,dem,runtime} \quad [30]$$

$$LFUELC_{tec,vtime,dem,runtime} = \left(pff_{tec,runtime} + emfCO2_{tec} \cdot txcarb_{tec,runtime}\right) \cdot FUEL_{tec,vtime,dem,runtime} \cdot \left(\frac{\sum_{vtime,dem} FUEL_{tec,vtime,dem,runtime}}{fuel0_{tec}}\right)^{nlpow_{tec}} \quad [31]$$

$$FC_{tec,runtime} = \left[\left(\overline{pINVT_{tec,runtime}}\right)\right] \cdot discrt_{tec} \cdot \frac{(1 + discrt_{tec})^{lifetime_{tec}}}{((1 + discrt_{tec})^{lifetime_{tec}} - 1)} \quad [32]$$

$$POWDM_{dem,butime} = \sum_{pr} loadprof_{pr,\mathrm{dem},runtime} \cdot dem1_{pr} \cdot \left(1 + bugrt_{butime,t_s}\right)^{butime-1} + loadprof_{hsh,\mathrm{dem},runtime} \cdot dem_{hsh} \cdot \left(1 + bugrt_{butime,t_s}\right)^{butime-1} + loadprof_{gov,\mathrm{dem},runtime} \cdot dem1_{gov} \cdot \left(1 + bugrt_{butime,t_s}\right)^{butime-1} + loadprof_{inv,\mathrm{dem},runtime} \cdot dem1_{inv} \cdot \left(1 + bugrt_{butime,t_s}\right)^{butime-1} + loadprof_{ex,\mathrm{dem},runtime} \cdot dem_{ex} \cdot \left(1 + bugrt_{butime,t_s}\right)^{butime-1} \quad [33]$$

$$\sum_{tec,vtime} GEN_{tec,vtime,dem,runtime} \geq POWDM_{tem,runtime} \perp pDM_{dem,runtime} \quad [34]$$

$$\sum_{tec,vtime} \left(KAVCT_{tec,vtime} - decom_{tec,vtime,\mathrm{runtime}}\right) \cdot util_{tec,dem,vtime} \geq POWDM_{tec,runtime} \cdot \left(1 + rm_{dem,runtime}\right) \perp pRM_{dem,runtime} \quad [35]$$

$$energymax_{hydro,runtime} \geq \sum_{dem,vtime} dur_{dem} \cdot GEN_{hydro,vtime,dem,runtime} \perp pHE_{hydro,runtime} \quad [36]$$

$$\sum_{tec,vtime} \left(KAVCT_{tec,vtime} - decom_{tec,vtime,\mathrm{runtime}}\right) \cdot util_{tec,vtime,dem} \geq GEN_{tec,vtime,dem,runtime} \perp pKT_{tec,vtime,dem,runtime} \quad [37]$$

where the following set abbreviations are used:

tec: Power generation technologies (coal, oil, wind, etc.)

$hydro$: Hydroelectric units

$vtime$: Unit installation time

dem: zone-time segments of load duration curve

$runtime, butime$: Time horizon of the bottom-up model

hsh: Households

gov: Government

inv: Investments

ex: Exports

Variables used are defined as follows:

$FUEL_{tec,vtime,dem,runtime}$: Fuel demand by tec units, installed in $vtime$ operating in demand zone dem in year $runtime$

$GEN_{tec,vtime,dem,runtime}$: Production of unit tec, constructed in year $vtime$ operating in demand zone dem in year $runtime$

$KAVCT_{tec,vtime}$: Unit capacity by tec installed in year $vtime$

$POWDM_{dem,butime}$: Power demand in zone dem in year $butime$

$FC_{tec,runtime}$: Annualized fixed cost payments of unit $tech$ that operates in year $runtime$

$NLFUELC_{tec,vtime,dem,runtime}$: Fuel cost

$pRM_{dem,runtime}$: Price of reserves (\$/MW)

$pDM_{dem,runtime}$: System marginal price (\$/MW)

$pKT_{tec,vtime,dem,runtime}$: Dual variable on capacity constraint (Rents producers earn from exhausting their capacity)

$pHE_{hydro,runtime}$: Dual variable on the constraint of total production of hydroelectric units (Rents that hydroelectric units earn when exhaust total annual water stocks are exhausted-\$/MW)

Parameters used are defined as follows:

δ: Discount rate

$vomc_{tec,runtime}$: Variable cost of production for unit tec operating in year $runtime$

$invnl_{tec,vtime}$: Fixed parameter that determines the speed of investment cost rise in unit tec constructed in year $vtime$

$pot_{tec,vtime}$: Maximum power potential of unit tec constructed in year $vtime$

$util_{tec,dem,vtime}$: Utilization factor of capacity of unit tec that operates in demand zone dem constructed in year $vtime$

$heatrate_{tec,vtime,dem,runtime}$: Thermal efficiency rate of unit tec, constructed in year $vtime$ operating in demand zone dem, in year $runtime$

dur_{dem}: Duration of demand zone dem (hours)

$scalef_{tec,rtime}$: Marginal cost scale parameter depending on the fuel quantity of unit tec

$pff_{tec,runtime}$: Fuel purchase price of unit tec operating in year $runtime$

$nlpow_{tec,runtime}$: Marginal cost elasticity parameter of unit tec operating in year $runtime$

$discrt_{tec}$: Depreciation rate of unit tec

$lifetime_{tec}$: Lifetime of unit tec

$bugrt_{butime,runtime}$: Demand increase rate in subsequent years ($butime$) compared to the demand in first year t_s

$loadprof_{pr,\mathrm{dem},runtime}$: Load profile parameter of sector pr determining the demand of zone dem, in year $runtime$

$loadprof_{hsh,\mathrm{dem},runtime}$: Load profile parameter of representative consumer determining the demand of zone dem, in year $runtime$

$loadprof_{gov,\mathrm{dem},runtime}$: Load profile parameter of government determining the demand of zone dem, in year $runtime$

$loadprof_{inv,\mathrm{dem},runtime}$: Load profile parameter of investment sector determining the demand of zone dem, in year $runtime$

$loadprof_{ex,\mathrm{dem},runtime}$: Load profile parameter of exports determining the demand of zone dem, in year $runtime$

dem_{pr}: Electricity Demand of producer pr (MWh)

dem_{hsh}: Electricity demand of representative consumer (MWh)

dem_{gov}: Electricity demand of government (MWh)

$emfCO2_{tec}$: Emission factor per fuel technology

$decom_{tec,vtime,runtime}$: Capacity of unit tec constructed in year $vtime$ and withdrawn in year $runtime$

$\overline{pINVT_{tec,runtime}}$: Investment price

$\overline{\overline{IPI_{runtime}}}$: Investment price index for the power generation module

It should be noted that the following condition applies: $vtime \leq ts \leq runtime \leq lstyear$ with ts: first year (it can dynamically change) and $lstyear$: last year for model solving (it can dynamically change).

TRANSFORMATION OF NLP TO MCP

The non-linear programming problem can be formulated into a mixed-complementarity problem, following the equation system structure proposed by Rutherford (1995). Two groups of production functions are used that determine when an existing unit will add to power generation and when a new unit will be constructed. The formulation of the mixed-complementarity problem is provided below with a brief description of the equations used.

The marginal fuel cost of each producer is given by:

$$mpF_{tec,vtime,dem,runtime} = \left(\frac{1}{1+\delta}\right)^{runtime-ts} \cdot \left(pff_{tec,runtime} + emfCO2_{tec} \cdot txcarb_{tec,runtime}\right) \cdot \left[\left(\frac{\sum_{vtime,dem} FUEL_{tec,vtime,dem,runtime}}{fuel0_{tec}}\right)^{nlpow_{tec}} + \frac{FUEL_{tec,vtime,dem,runtime}}{fuel0} \cdot \left(\frac{\sum_{vtime,dem} FUEL_{tec,vtime,dem,runtime}}{fuel0_{tec}}\right)^{nlpow_{tec}-1}\right] \cdot heatrate \cdot dur_{dem} \perp mpF_{tec,vtime,dem,runtime} \quad [38]$$

where:

$txcarb_{tec,runtime}$: Carbon tax

The annualized cost of the construction of a new unit is given by:

$$mpFC_{tec,runtime}\left[\left(\overline{pINVT_{tec,runtime}}\right)\right] \cdot discrt_{tec} \cdot \frac{(1+discrt_{tec})^{lifetime_{tec}}}{((1+discrt_{tec})^{lifetime_{tec}}-1)} \perp mpFC_{tec,runtime} \quad [39]$$

The required then fuel quantity is given by:

$$FUEL_{tec,vtime,dem,runtime} = heatrate_{tec,vtime,dem,runtime} \cdot dur_{dem} \cdot GEN_{tec,vtime,dem,runtime} \perp FUEL_{tec,vtime,dem,runtime} \quad [40]$$

The production cost for each producer is given by:

$$mpF_{tec,vtime,dem,runtime} + \left(\frac{1}{1+\delta}\right)^{runtime-ts} \cdot vomc_{tec,runtime} + pKT_{tec,vtime,dem,runtime} + pHE_{tec\in hydro,runtime} \geq pDM_{dem,runtime} \quad \perp GEN_{tec,vtime,dem,runtime} \quad [41]$$

Construction of new sites is given by the equation below. Total construction cost of new production sites should be covered by total rents accrued.

$$\sum_{runtime\geq vtime} \left(\frac{1}{1+\delta}\right)^{runtime-ts} \cdot (mpFC_{tec,runtime} - invnl_{tec,vtime} \cdot \log(1-\frac{KAVCT_{tec,vtime}}{pot_{tec,vtime}})) \geq \sum_{runtime\geq vtime,dem} pKT_{tec,vtime,dem,runtime} \cdot dur_{dem} \cdot util_{tec,dem,vtime} + \sum_{runtime\geq vtime,dem} pRM_{dem,runtime} \cdot util_{tec,dem,vtime} \quad [42]$$

Power demand in each demand zone is given by:

$$POWDM_{dem,butime} = \sum_{pr} loadprof_{pr,dem,runtime} \cdot dem1_{pr} \cdot (1 + bugrt_{butime,t_s})^{butime-1} + loadprof_{hsh,dem,runtime} \cdot dem_{hsh} \cdot (1 + bugrt_{butime,t_s})^{butime-1} + loadprof_{gov,dem,runtime} \cdot dem1_{gov} \cdot (1 + bugrt_{butime,t_s})^{butime-1} + loadprof_{inv,dem,runtime} \cdot dem1_{inv} \cdot (1 + bugrt_{butime,t_s})^{butime-1} + loadprof_{ex,dem,runtime} \cdot dem_{ex} \cdot (1 + bugrt_{butime,t_s})^{butime-1} \perp POWDM_{dem,butime} \quad [43]$$

Clearing condition for power demand is formulated as follows:

$$\sum_{tec,vtime} GEN_{tec,vtime,dem,runtime} \geq POWDM_{tem,runtime} \perp pDM_{dem,runtime} \quad [44]$$

The constraint on stock capacity required is given by:

$$\sum_{tec,vtime} \left(KAVCT_{tec,vtime} - decom_{tec,vtime,runtime}\right) \cdot util_{tec,dem,vtime} \geq POWDM_{tec,runtime} \cdot \left(1 + rm_{dem,runtime}\right) \perp pRM_{dem,runtime} \quad [45]$$

Capacity limits for power producers is given by:

$$\sum_{tec,vtime} \left(KAVCT_{tec,vtime} - decom_{tec,vtime,runtime}\right) \cdot util_{tec,dem,vtime} \geq GEN_{tec,vtime,dem,runtime} \perp pKT_{tec,vtime,dem,runtime} \quad [46]$$

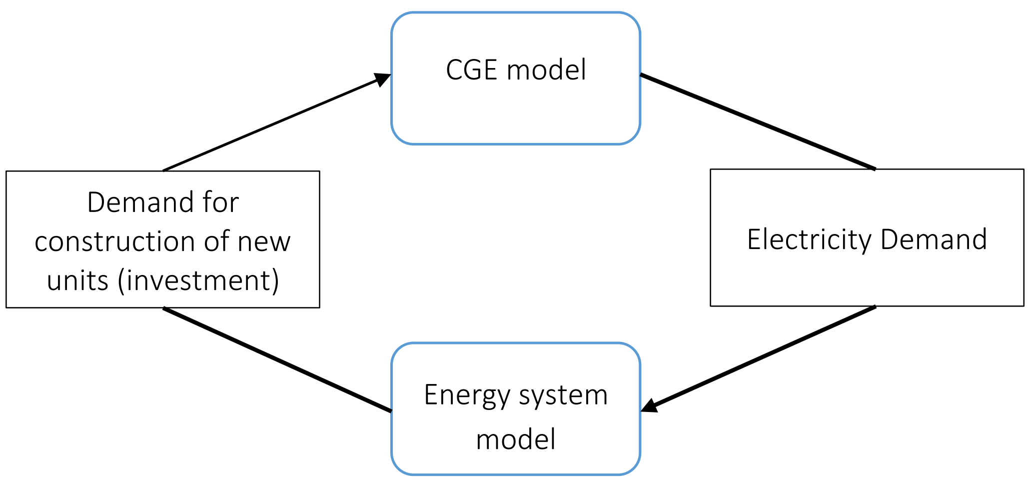
Water resources constraint for hydroelectric units is given by:

$$energymax_{hydro,runtime} \geq \sum_{dem,vtime} dur_{dem} \cdot GEN_{hydro,vtime,dem,runtime} \perp pHE_{hydro,runtime}$$ [47]

HYBRID MODEL

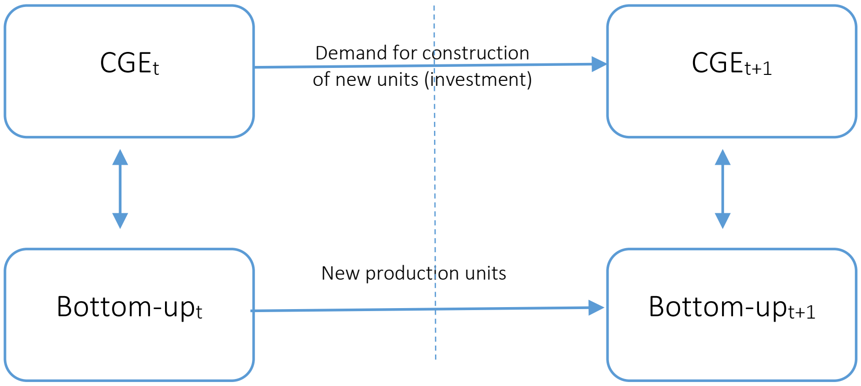
This section discusses how a detailed representation of the power generation sector can be integrated into a macroeconomic model. In this setting the CGE model provides a detailed energy system model input on the prices of intermediate goods and inputs required from the power generation technologies, electricity demand, and the cost of construction of new production units (Figure 13). In its turn, the bottom-up model, given the power demand and information of preferences of consumers, constructs a load duration curve with 11 time zones that differentiate in the amount of energy required. The bottom-up module provides as input to the macroeconomic model an average annual cost of electricity generation, demand for production inputs as resulting from the operation of production units and the investments undertaken by each technology.

Figure 13: Top-down and bottom-up model links



When the module is solved the investments decided in time *t* become operational units in time *t+5* with capacity equal to that determined in module solution in year *t*. In other words investments undertaken in a 5-year time period produce a stock of capital available in the following period. The dynamic properties of the model are illustrated in Figure 14. Model equations for the power generation sector are formulated as summarized below.

Figure 14: Dynamic properties of bottom-up top-down model



Marginal cost of production of the power generation sector is given by:

$$pD_{ele,t} = \frac{pd_{ele,0}}{tfp_t} \cdot \left[\theta_{t\&d,t} \cdot \frac{pDIST_{ele,t}}{pdist_{ele,0}} + \theta_{sup,t} \cdot \frac{pSUP_{ele,t}}{psup_{ele,0}}\right] \quad [48]$$

Marginal cost of transmission and distribution sector is given by:

$$pDIST_{ele,t} = pdist_{ele,0} \cdot \left[\sum_{\forall pr} distco_{pr} \cdot e^{-tge0_{pr\in ene,t}} \cdot \frac{pIO_{pr,t}}{pio_{pr,0}} + distcol \cdot \frac{pL_t}{pl_0} + distcok \cdot \frac{pK_t}{pk_0}\right] \quad [49]$$

Demand for transmission and distribution is given by:

$$\mathrm{DIST}_{\mathrm{ele,t}} = \left[\sum_{\forall pr} XXDELEpr_{pr,t} + XXDELEhsh_{hsh,t} + XXDELEgov_{gov,t} + XXDELEinv_{inv,t} + XXDELEex_{ex,t}\right] \quad [50]$$

where:

$XXDELEpr_{pr,t}$, $XXDELEhsh_{hsh,t}$, $XXDELEgov_{gov,t}$, $XXDELEinv_{inv,t}$, $XXDELEex_{ex,t}$ demand of production sectors (producers, *pr*), households, government, investments and exports respectively.

In the following step the equations of the power generation module are rewritten, but in this step the exogenous prices and quantities have been replaced by the respective prices and quantities computed with the macroeconomic module.

$$mpF_{tec,vtime,dem,runtime} = \left(\frac{1}{1+\delta}\right)^{runtime-ts} \cdot \sum_{pr \in mapinptec_{pr,tec}} \left(pIO_{pr,t} + emfCO2_{tec} \cdot txcarb_{pr,runtime}\right) \cdot \left[\left(\frac{\sum_{vtime,dem} FUEL_{tec,vtime,dem,runtime}}{fuel0_{tec}}\right)^{nlpow_{tec}} + nlpow_{tec} \cdot \frac{FUEL_{tec,vtime,dem,runtime}}{fuel0} \cdot \left(\frac{\sum_{vtime,dem} FUEL_{tec,vtime,dem,runtime}}{fuel0_{tec}}\right)^{nlpow_{tec}-1}\right] \cdot heatrate \cdot dur_{dem} \perp mpF_{tec,vtime,dem,runtime} \quad [51]$$

$$mpFC_{tec,runtime} = \frac{\left[pINVT_{tec,\mathrm{runtime}}\right] \cdot discrt_{tec} \cdot (1 + discrt_{tec})^{lifetime_{tec}}}{\left((1 + discrt_{tec})^{lifetime_{tec}} - 1\right)} \perp mpFC_{tec,runtime} \quad [52]$$

$$FUEL_{tec,vtime,dem,runtime} = heatrate_{tec,vtime,dem,runtime} \cdot dur_{dem} \cdot GEN_{tec,vtime,dem,runtime} \perp FUEL_{tec,vtime,dem,runtime} \quad [53]$$

$$mpF_{tec,vtime,dem,runtime} + \left(\frac{1}{1+\delta}\right)^{runtime-ts} \cdot vomc_{tec,0} \cdot \sum_{\forall pr}(vomcco_{pr,tec} \cdot e^{-tge0_{pr\in ene,t}} \cdot \frac{pIO_{pr,t}}{pio_{pr,0}} + vomccol_{tec} \cdot \frac{pL_t}{pl_0}) + pKT_{tec,vtime,dem,runtime} + pHE_{tec\in hydro,runtime} \geq pDM_{dem,runtime} \perp GEN_{tec,vtime,dem,runtime}$$ [54]

$$\sum_{runtime\geq vtime} \left(\frac{1}{1+\delta}\right)^{runtime-ts} \cdot (mpFC_{tec,runtime} - invnl_{tec,vtime} \cdot (\frac{IPI_{runtime}}{ipi_0}) \cdot \log(1 - \frac{KAVCT_{tec,vtime}}{pot_{tec,vtime}})) \geq \sum_{runtime\geq vtime,dem} pKT_{tec,vtime,dem,runtime} \cdot dur_{dem} \cdot util_{tec,dem,vtime} + \sum_{runtime\geq vtime,dem} pRM_{dem.runtime} \cdot util_{tec,dem,vtime}$$ [55]

$$POWDM_{dem,butime} = \Bigg[\sum_{pr,t} loadprof_{pr,dem,runtime} \cdot XXDELEpr_{pr,t} \cdot \left(1 + bugrt_{butime,t_s}\right)^{butime-1} + \sum_{\forall t} loadprof_{hsh,dem,runtime} \cdot XXDELEhsh_{hsh,t} \cdot \left(1 + bugrt_{butime,t_s}\right)^{butime-1} + \sum_{\forall t} loadprof_{gov,dem,runtime} \cdot XXDELEgov_{gov,t} \cdot \left(1 + bugrt_{butime,t_s}\right)^{butime-1} + \sum_{\forall t} loadprof_{inv,dem,runtime} \cdot XXDELEinv_{inv,t} \cdot \left(1 + bugrt_{butime,t_s}\right)^{butime-1} + \sum_{\forall t} loadprof_{ex,dem,runtime} \cdot XXDELEex_{ex,t} \cdot \left(1 + bugrt_{butime,t_s}\right)^{butime-1}\Bigg] \cdot \theta_{sup,t} \cdot \left(\frac{\frac{pd_{ele,0}}{tfp_t}}{psup0_{ele,t}}\right) \perp POWDM_{dem,butime} \qquad [56]$$

$$\sum_{tec,vtime} GEN_{tec,vtime,dem,runtime} \geq POWDM_{dem,runtime} \perp pDM_{dem,runtime} \qquad [57]$$

$$\sum_{tec,vtime} \left(KAVCT_{tec,vtime} - decom_{tec,vtime,runtime}\right) \cdot util_{tec,dem,vtime} \geq POWDM_{tec,runtime} \cdot \left(1 + rm_{dem,runtime}\right) \perp pRM_{dem,runtime} \qquad [58]$$

$$\sum_{tec,vtime} \left(KAVCT_{tec,vtime} - decom_{tec,vtime,runtime}\right) \cdot util_{tec,dem,vtime} \geq GEN_{tec,vtime,dem,runtime} \perp pKT_{tec,vtime,dem,runtime} \quad [59]$$

$$energymax_{hydro,runtime} \geq \sum_{dem,vtime} dur_{dem} \cdot GEN_{hydro,vtime,dem,runtime} \perp pHE_{hydro,runtime} \quad [60]$$

The price for the power generation sector is given by:

$$\sum_{tec,vtime,dem} dur_{dem} \cdot GEN_{tec,vtime,dem,t} \cdot \mathrm{pSUP_{ele,t}} = \sum_{tec,vtime,dem} \left[\sum_{pr \in mapinptec_{pr,tec}} \left(pIO_{pr,t} \cdot FUEL_{pr,t}\right) + vomc_{tec,0} \cdot \sum_{\forall pr} \left(vomcco_{pr,tec} \cdot e^{-tge0_{pr\in ene,t}} \cdot \frac{pIO_{pr,t}}{pio_{pr,0}} + vomccol_{tec} \cdot \frac{pL_t}{pl_0} \right) + pKT_{tec,vtime,dem,t} + pHE_{tec\in hydro,t} \right] \cdot dur_{dem} \cdot GEN_{tec,vtime,dem,t} + \sum_{tec,vtime} mpFC_{tec,runtime} \cdot KAVCT_{tec,vtime} \perp \mathrm{pSUP_{ele,t}} \quad [61]$$

Last are defined the unit conversion variables that make both modules compatible as well as the variables that set the demand for intermediate goods, inputs to production (labour, capital) and power generation sector investments as follows:

Marginal cost of construction of new power generation units is formulated as follows:

$$pINVT_{tec,t} = \sum_{\forall prr} techdinvt_{prr,tec} \cdot e^{-tge0_{pr\in ene,t}} \cdot pINVP_{prr,t} \quad [62]$$

Investments in year t are formulated as follows:

$$INVT_{tec,t} = KAVCT_{tec,t+5} \quad [63]$$

Investment in capital requirements of the power generation sector are formulated as follows:

$$INVTBU_t = \sum_{tec} pINVT_{tec,t} \cdot INVT_{tec,t} \quad [64]$$

Demand for intermediate inputs for the construction of new power generation sites is given by:

$$INVTV_{pr,tec,t} = techdinvt_{pr,tec} \cdot e^{-tge0_{pr\in ene,t}} \cdot \left(\frac{pinvt_{tec,0}}{pinvp_{pr,0}}\right) \cdot INVT_{tec,t} \quad [65]$$

Demand for labour of the power generation sector is given by:

$$LAVTBU_{ele,t} = DIST_{ele,t} \cdot distcol \cdot \left(\frac{pdist_0}{pl_0}\right) + \sum_{tec,vtime,dem} \left(\frac{vomc}{pl_0}\right) \cdot vomccol_{tec} \cdot dur_{dem} \cdot GEN_{tec,vtime,dem,t} \quad [66]$$

Consumers' rents from the power generation sector are formulated as follows:

$$KAVTBU_{ele,t} = \sum_{tec,vtime,dem} pKT_{tec,vtime,dem,t} \cdot dur_{dem} \cdot GEN_{tec,vtime,dem,t} + \sum_{tec\in hydro,vtime,dem} pHE_{tec\in hydro,vtime,dem,t} \cdot dur_{dem} \cdot GEN_{tec,vtime,dem,t} + \sum_{tec,vtime} mpFC_{tec,runtime} \cdot KAVCT_{tec,vtime} \quad [67]$$

Demand for intermediate goods from power generation sector is given by:

$$IOVTBU_{pr,ele,t} = DIST_{ele,t} \cdot distco \cdot e^{-tge0_{pr\in ene,t}} \cdot \left(\frac{pdist_0}{pio_{pr,0}}\right) + \sum_{tec\in mapinptec_{pr,tec},vtime,dem} FUEL_{tec,vtime,dem,t} + + \sum_{tec,vtime,dem} \left(\frac{vomc}{pio_{pr,0}}\right) \cdot vomcco_{pr,tec} \cdot e^{-tge0_{pr\in ene,t}} \cdot dur_{dem} \cdot GEN_{tec,vtime,dem,t} \quad [68]$$

Producers' demand for power (in MWh) is formulated as follows:

$$XXDELEpr_{ele,br,t} = \left(IOV_{ele,br,t}\right) \cdot \theta_{xxd} \cdot \left(\frac{\frac{pY_{ele,t}}{py_{ele,0}}}{\frac{pXXD_{ele,t}}{pxxd_{ele,0}}}\right)^{sxdw_{pr}} \cdot \left(\frac{py_{ele,0}}{pxxd_{ele,0}}\right)^{1-sxdw_{pr}} + \left(IOVTBU_{ele,br\in ele,t}\ \right) \cdot \theta_{xxd} \cdot \left(\frac{\frac{pY_{ele,t}}{py_{ele,0}}}{\frac{pXXD_{ele,t}}{pxxd_{ele,0}}}\right)^{sxdw_{pr}} \cdot \left(\frac{py_{ele,0}}{pxxd_{ele,0}}\right)^{1-sxdw_{pr}} \quad [69]$$

Demand for power (in MWh) from the representative household is formulated as follows:

$$XXDELEhsh_{hsh,t} = \left(HCV_{ele,t} \cdot\ \right) \cdot \theta_{xxd} \cdot \left(\frac{\frac{pY_{ele,t}}{py_{ele,0}}}{\frac{pXXD_{ele,t}}{pxxd_{ele,0}}}\right)^{sxdw_{pr}} \cdot \left(\frac{py_{ele,0}}{pxxd_{ele,0}}\right)^{1-sxdw_{pr}} \quad [70]$$

Demand for power (in MWh) from the government is formulated as follows:

$$XXDELEgov_{gov,t} = \left(GCV_{ele,t}\right) \cdot \theta_{xxd} \cdot \left(\frac{\frac{pY_{ele,t}}{py_{ele,0}}}{\frac{pXXD_{ele,t}}{pxxd_{ele,0}}}\right)^{sxdw_{pr}} \cdot \left(\frac{py_{ele,0}}{pxxd_{ele,0}}\right)^{1-sxdw_{pr}} \quad [71]$$

Demand for power (in MWh) from investments is formulated as follows:

$$XXDELEinv_{inv,t} = \left(HCV_{ele,t}\right) \cdot \theta_{xxd} \cdot \left(\frac{\frac{pY_{ele,t}}{py_{ele,0}}}{\frac{pXXD_{ele,t}}{pxxd_{ele,0}}}\right)^{sxdw_{pr}} \cdot \left(\frac{py_{ele,0}}{pxxd_{ele,0}}\right)^{1-sxdw_{pr}} \quad [72]$$

Last, demand for power for exports (in MWh) is given by:

$$XXDELEex_{ex,t} = \left(EXPO_{ele,t}\right) \cdot \theta_{xxd} \cdot \left(\frac{\frac{pY_{ele,t}}{py_{ele,0}}}{\frac{pXXD_{ele,t}}{pxxd_{ele,0}}}\right)^{sxdw_{pr}} \cdot \left(\frac{py_{ele,0}}{pxxd_{ele,0}}\right)^{1-sxdw_{pr}} \quad [73]$$

where:

$mapinptec\_(pr, tec)$: Parameter matching fuel types with power generation technologies using them

$techdinvt_{prr,tec}$: Exogenously set technical coefficient of capital construction sector

$vomcco_{pr,tec}$: Value share of intermediate good pr in variable cost of technology tec

$vomccol_{tec}$: Value share of labour in variable cost of technology tec

In the macroeconomic model the following equations apply:

Demand for products from the power generation section is formulated as follows:

$$IOV_{pr,ele,t} = IOVTBU_{pr,ele,t} \quad [74]$$

Demand for labour, constrained by total labour supply available, is given by:

$$LAVC_t \geq \sum_{pr} LAV_{pr,t} + LAVTBU_{ele,t} \perp pL_t \quad [75]$$

Last household income is given by:

$$INCHS_t = \sum_{pr} pK_t \cdot KAV_{pr,t} + pL_t \cdot LAV_{pr,t} + pRS_{pr,t} \cdot RESC_{pr,t} + KAVTBU_{ele,t} \quad [76]$$

The macroeconomic IS-LM condition is formulated as follows:

$$\sum_{pr} pINV_{pr,t} \cdot INVV_{pr,t} + INVTBU_{ele,t} = SAV_t \perp RLTLR_t \quad [77]$$

In this way the equilibrium condition in the power generation market is incorporated in the general equilibrium context where several markets (labour, goods, etc.) simultaneously reach equilibrium. Thus the approach consists of an equilibrium problem with equilibrium constraints (see Gabriel et al., 2012).

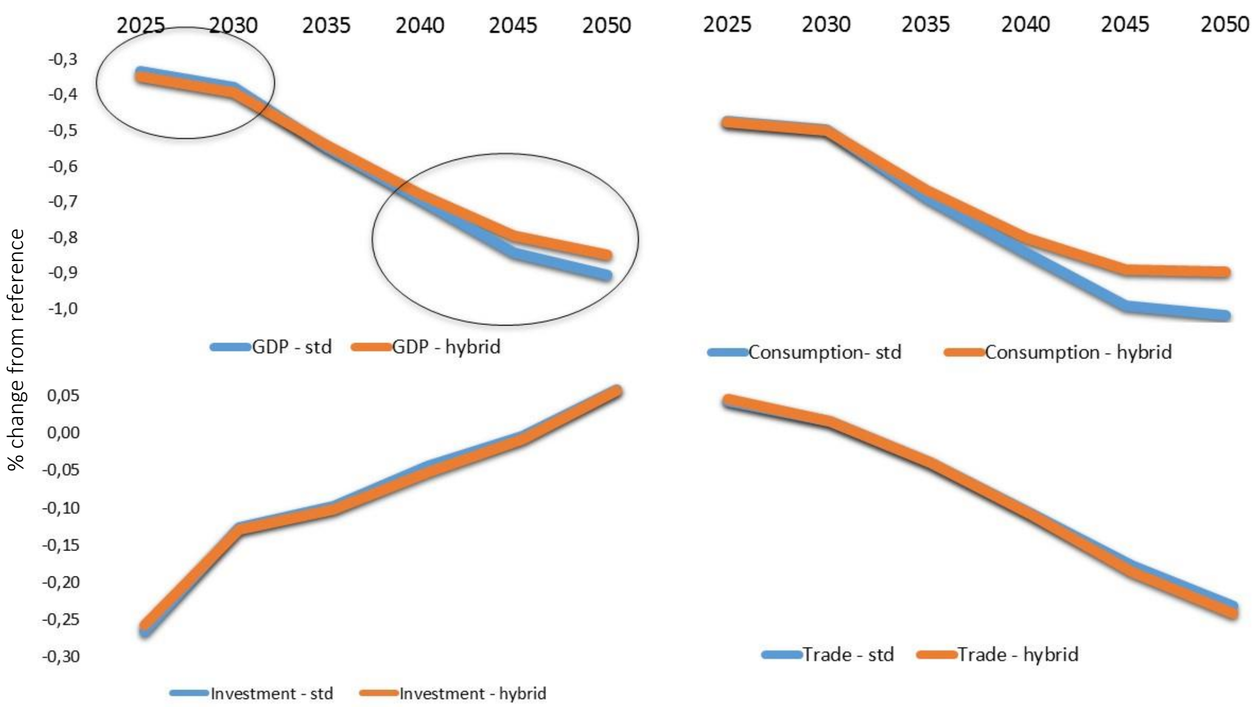
The above mentioned bottom-up representations have been included in the GEM-E3 model and two alternative reference scenarios have been quantified, each with a different representation of the power generation sector (a "typical" approach and a "detailed"). In order to illustrate the properties of the proposed modelling approaches a scenario with escalating carbon taxes (Table 9) was simulated.

Table 9: Carbon tax

	2025	2030	2035	2040	2045	2050
Carbon Tax (in €2010)	38	68	105	150	195	225

In modelling terms, a carbon tax was imposed in all GHG emitting activities, letting the model itself suggest how the agents internalize such a cost into their production-consumption structures and choices. The carbon tax acts additionally to the baseline scenario assumptions, triggering structural changes and substitutions. This tax is an additional cost to the firms and households and associates those costs to final and intermediate consumption goods that emit GHG emissions.

Figure 15: EU28 Macroeconomic adjustment when different power sector representations are considered



Source: GEM-E3-ADVANCE

The model version with the typical representation of the power generation sector (i.e. nested CES function of electricity) substitutes imported fuels (mainly coal and oil) with primary production factors (capital and labour) which are produced mainly domestically. The substitution is limited by the KL – Energy substitution elasticity which in the current model setup is set to 0.25. The capital cost in this case does not reflect the RES capital costs as it is a unit cost that is derived from the capital market clearing. For low carbon taxes this formulation tends to underestimate the costs whereas the limited substitution possibilities (fixed capital supply over the period) will tend to overestimate the adjustment costs for high carbon taxes (Figure 15).

REFERENCES

Andersen, K., S. and Termansen, L., B. (2013). Bottom-up and top-down modelling approach, Interact model, Working Paper No. 04.

Bauer N., Edenhofer, O. and Kypreos, S. (2007). Linking energy system and macroeconomic growth models, Computational Management Science, 5(1), 95-117.

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

Böhringer, C., Hoffmann, T. and Loeschel, A. (2003). Dismantling nuclear power in Europe: Macroeconomic and environmental impacts. ZEW Discussion Paper No. 03-15, University of Mannheim.

Böhringer, C., and Rutherford, T. (2006). Combining Top-Down and Bottom-Up in Energy policy analysis: A decomposition approach, ZEW Discussion Paper, No 06-007.

Böhringer C. and Rutherford T.F. (2009). Integrated assessment of energy policies: Decomposing top-down and bottom-up, Journal of Economic Dynamics and Control, 33, 1648–1661.

Catenazzi, G. (2009): Advances in techno-economic energy modeling: Costs, dynamics and hybrid aspects. Dissertation, Swiss Federal Institute of Technology (ETH), Zürich, Diss. ETH. No 18016.

Cottle, R., Pang, J. and Stone, E. (1992). The Linear Complementarity Problem, Academic Press, New York.

Dirkse, S. and Ferris, M. (1995). The path-solver: a non-monotone stabilization scheme for mixed complementarity problems. Optimization Methods and Software, 5, 123 – 156.

Gabriel,S.A., Conejo,A., J., Fuller, J.,D., Hobbs, B.,F. and Ruiz, C. (2012). Applied Complementary Models to Energy Markets for the First Time. Springer

Grubb, M., Edmonds, J., ten Brink, P., Morrison, M. (1993). The costs of limiting fossil-fuel CO2 emissions: A survey and analysis. Annual Review of Energy and the Environment 18, 397–478.

Frei, C.W., Haldi, P.A. and Sarlos, G. (2003). Dynamic formulation of a top-down and bottom-up merging energy policy model. Energy Policy 31, 1017–1031.

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(2), 461-514.

Hourcade, J.H., Jaccard, H., Bataille, C. and Ghersi, F. (2006). Hybrid modeling: New answers to old challenges, The Energy Journal, International Association for Energy Economics, 2, pp.1-12.

IPCC (1995). Climate change 1995: Economic and Social Dimensions of Climate Change. Cambridge University Press, Cambridge.

IPCC (2001). Climate Change 2001: Mitigation. Cambridge University Press, Cambridge.

Jochem, E., Barker, T., Scrieciu, S., Schade, W., Helfrich, N., Edenhofer, O., Bauer, N., Marchand, S., Neuhaus, J., Mima, S., Criqui, P., Morel, J., Chateau, B., Kitous, A., Nabuurs, G.J., Schelhaas, M.J., Groen, T., Riffeser, L., Reitze, F., Jochem, E., Catenazzi, G., Jakob, M., Aebischer, B., Kartsoni, K., Eichhammer, W., Held, A., Ragwitz, M., Reiter, U., Kypreos, S. and Turton, H. (2007): EU-Project ADAM: Adaption and Mitigation Strategies: Supporting European Climate Policy - Deliverable M1.1: Report of the Base Case Scenario for Europe and full description of the model system. Fraunhofer ISI, Karlsruhe, November 2007.

Koopmans, T. C. (1951). An analysis of production as an efficient combination of activities. In Koopmans, T. C. (Ed.), Activity Analysis of Production and Allocation. John Wiley and Sons, Inc.

Kumbaroglu, 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, Zurich.

Kumbaroglu, G. and Madlener, R. (2003). Energy and climate policy analysis with the hybrid bottom-up computable general equilibrium model SCREEN: the case of the Swiss CO2 Act. Annals of Operations Research 121, 181–203.

Mathiesen, L. (1985). Computation of economic equilibria by a sequence of linear complementarity problems. Mathematical Programming Study, 23, 144–162.

McDougall, R.A. "Entropy Theory and RAS are Friends." GTAP Working Paper No. 06 (1999). Accessed at: < https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=300>

McFarland, J., Reilly, J. and Herzog, H. (2002). Representing Energy Technologies in Top-down Economic Models Using Bottom-up Information. MIT Joint Program on the Science and Policy of Global Change, Report, vol. 89.

McFarland, J., Reilly, J. and Herzog, H., J. (2004). Representing energy technologies in top-down economic models using bottom-up information, Energy Economics, 26(4),687-707.

Messner S. and Schrattenholzer, L. (2000). MESSAGE-MACRO: Linking an energy supply model with a macroeconomic module and solving it iteratively, Energy, 25, 267-282.

Miess, M., G., Schmelzer, S. and Janke, J. (2014). Report on Improvements in the Hybrid General Equilibirum core model. Project: Development of an Evaluation Framework for the Introduction of Electromobility.

Muller, T. (2000). Integrating bottom-up and top-down models for energy policy analysis: A dynamic framework, Discussion paper No 00.02, Universite de Geneve, November 2000.

National Academy of Sciences (1991). Policy Implications of Greenhouse Warming. National Academies Press, Washington, DC.

Peters, C., J. (2015). The GTAP-Power Database: Disaggregating the Electricity Sector in the GTAP Database, Center for Global Trade Analysis, Purdue University, West Lafayette, USA.

Pressman, I. (1970). A mathematical formulation of the peak-load pricing problem. The Bell Journal of Economics and Management Science, 1, 304–326.

Rutherford, T.F. (1995). Extensions of GAMS for complementarity problems arising in applied economic analysis, Journal of Economic Dynamics and Control, 19, 1299-324.

Remme U. and Blesl, M. (2006). Documentation of the TIMES-MACRO model, Energy Technology Systems Analysis Programme. http://www.etsap.org.

Schafer, A. and Jacoby, H.D. (2006). Experiments with a Hybrid CGE-MARKAL Model. The Energy Journal, Special Issue, 171-177.

Takayma, T. and Judge, G. (1971). Spatial and Temporal Price and Allocation Models. North-Holland, Amsterdam.

Tapia-Ahumada, K., Octaviano, C., Rausch, S., and Perez-Arriaga, I. (2015). Modeling intermittent renewable electricity technologies in general equilibrium models, Economic Modelling, 51, 242-262.

Wilson, D. and Swisher, J. (1993). Exploring the gap: top-down versus bottom up analyses of the cost of mitigating global warming. Energy Policy 21, 249–263.

Wing, I. S. (2006). The synthesis of bottom-up and top-down approaches to climate policy modelling: Electric power technologies and the cost of limiting US CO2 emissions, Energy Policy, 34, 3847-3869.

ANNEX

LIST OF SETS

Set	Description
bupr	Dimensions of Extented IO table
bupre	Subset of fuels
buprele	Subset of electricity sector
buprma	Non energy sectors
buprt	Subset of power generation technologies
buprt_ma	Subset of power generation technologies that use materials
buprt_nom	Subset of power generation technologies that do not use materials
buprtf	Subset of power generation technologies that use fuels
cgd	Gross fixed capital formation
cott	Regions-Countries (model based)
dir	Identifier for imported or domestic
f	Primary factors
fa	Main production factors
fk	Factors assigned to capital
fl	Factors assigned to labour
i	Commodities
iea_cott	Regional aggregation in iea_prices
iea_flows	IEA flows in extended Energy Balance
iea_products	IEA products in extended Energy Balance
pcat	Different price categories
pg	Power generation technologies
pr	Products classification (model based)
ptec	Power generation technologies represented by the model
r	Regions
rcott	Countries to enter cross entropy
tecdat	TECHPOL data categories
time	Time

LIST OF PARAMETERS

Parameter	Dimension	Description
aedf	(pr,br,cott)	Aggregated usage of domestic product by firms, Mtoe
aedg	(pr,cott)	Aggregated Government consumption of domestic product, Mtoe
aedp	(pr,cott)	Aggregated Private consumption of domestic product, Mtoe
aeif	(pr,br,cott)	Aggregated Usage of imports by firms, Mtoe
aeig	(pr,cott)	Aggregated Government consumption of imports, Mtoe
aeip	(pr,cott)	Aggregated Private consumption of imports, Mtoe
aetf	(pr,br,cott)	Aggregated Total use of energy by firms, Mtoe
aetg	(pr,cott)	Aggregated Government consumption of energy, Mtoe
aetp	(pr,cott)	Aggregated Private consumption of energy, Mtoe
amdf	(pr,br,cott)	Aggregated CO2 emissions by firms (domestic)
amdg	(pr,cott)	Aggregated CO2 emissions by Government consumption (domestic)
amdp	(pr,cott)	Aggregated CO2 emissions by Private consumption (domestic)
amif	(pr,br,cott)	Aggregated CO2 emissions by firms (imports)
amig	(pr,cott)	Aggregated CO2 emissions by Government consumption (imports)
amip	(pr,cott)	Aggregated CO2 emissions by Private consumption (imports)
amtf	(pr,br,cott)	Aggregated Total CO2 emissions by firms
amtg	(pr,cott)	Aggregated Government consumption CO2 emissions
amtp	(pr,cott)	Aggregated Private consumption CO2 emissions
buio_fin	(*,*,cott)	Bottom-up Input Output Table, Final
buio_ini	(*,*,cott)	Bottom-up Input Output Table, Initial
cnt	(pg,cott)	Construction time, in years
congjmwh		Conversion GJ to MWh (3.6)
drt	(cott)	Discount rate
dsh	(pg,cott)	Decommission share, in %
edf	(i,j,r)	Usage of domestic product by firms, Mtoe
edg	(i,r)	Government consumption of domestic

		product, Mtoe
edp	(i,r)	Private consumption of domestic product, Mtoe
eel	(pg,cott)	Electrical efficiency, in %
eif	(i,j,r)	Usage of imports by firms, Mtoe
eig	(i,r)	Government consumption of imports, Mtoe
eip	(i,r)	Private consumption of imports, Mtoe
eleout	(ptec,cott)	Production of electricity by technology, GWh
energy_vol	(bubr,cott)	Energy volume per power generation technology, Mtoe
envol_gc	(bupr,*,cott)	Energy volume Intermediate Demand, Mtoe
envol_hc	(bupr,*,cott)	Energy volume Intermediate Demand, Mtoe
envol_io	(bupr,bubr,cott)	Energy volume Intermediate Demand, Mtoe
evfa	(f,i,r)	Factor payments at agent prices
evoa	(f,r)	Value of factor income at national level
exr		Exchange rate, $/€
fbep	(f,j,r)	Factor based subsidies
fct	(pg,cott)	Fuel cost, in €/MWh
fom	(pg,cott)	Fixed O&M, in €/kWy
ftrv	(f,j,r)	Factor taxes
fuel_price	(bubr,cott)	Fuel price (million $) per Mtoe
iea_prices	(iea_cott,pcat)	US dollar per Gj
isep	(j,i,r,dir)	Net taxes on sales
ka_ini	(cott)	Operating surplus of PG and T&D
kct	(pg,cott)	Capital cost, in €/MWh
la_ini	(cott)	Compensation of employees of PG and T&D
lfc	(pg,cott)	Load factor, in %
market_share_target	(bupr,cott)	Market share constraints given by the energy balances
mdf	(i,j,r)	CO2 emissions by firms (domestic)
mdg	(i,r)	CO2 emissions by Government consumption (domestic)
mdp	(i,r)	CO2 emissions by Private consumption (domestic)
mfrv	(j,r,s)	Export subsidy
mif	(i,j,r)	CO2 emissions by by firms (imports)
mig	(i,r)	CO2 emissions by Government consumption (imports)
mip	(i,r)	CO2 emissions by Private consumption (imports)
no_eleout	(cott)	Countries without data on energy balances
oic	(pg,cott)	Overnight Investment Cost, in €2010/kw
osep	(i,r)	Tax on production (ordinary output subsidy)

penval_gc	(bupr,*,cott)	Energy prices, Intermediate Demand, $/Mtoe
penval_hc	(bupr,*,cott)	Energy prices, Intermediate Demand, $/Mtoe
penval_io	(bupr,bubr,cott)	Energy prices, Intermediate Demand, $/Mtoe
price_tec_fct	(bubr,cott)	Fuel Cost of power generation technologies, $/MWh
price_tec_fom	(bubr,cott)	Labour Cost of power generation technologies, $/MWh
price_tec_kct	(bubr,cott)	Capital Cost of power generation technologies, $/MWh
price_tec_tcp	(bubr,cott)	Price of power generation technologies
price_tec_vom	(bubr,cott)	Material Cost of power generation technologies, $/MWh
production_share_target	(fa,bupr,cott)	Production structure of pg technologies
rir	(cott)	Real interest rate
techpol_fct	(pg,cott)	Fuel Cost, in $/ MWh
techpol_fom	(pg,cott)	Fixed O&M cost, in $/ MWh
techpol_kct	(pg,cott)	Capital cost, in $/MWh
techpol_vom	(pg,cott)	Variable O&M, in $/MWh
techpolii_data	(pg,tecdat,time)	Data on power generation technologies from TECHPOLII
tef	(pg,cott)	Thermal efficiency, in %
tfrv	(j,s,r)	Bilateral duties
tic	(pg,cott)	Total Investment cost, in €2010/kW
tlf	(pg,cott)	Technical lifetime, in years
tpc	(pg,cott)	Total production cost, in €/MWh
vafa	(j,i,r)	Composite intermediate use agent price
vafm	(j,i,r)	Composite intermediate use market price
vdep	(r)	Capital depreciation
vdfa	(i,j,r)	Expenditure on inter goods domestic. prod agent prices
vdfm	(i,j,r)	Expenditure on inter goods domestic. prod market prices
vdga	(i,r)	Value of domestic goods, government consumption at agent prices
vdgm	(i,r)	Government expenditure on domestically produced goods
vdpa	(i,r)	Value of domestic goods, household consumption at agent prices
vdpm	(i,r)	Private expenditure on domestically produced goods
vfm	(f,i,r)	Payment to primary factors (market prices)
vifa	(i,j,r)	Expenditure on intermediate goods, imported agent prices

vifm	(i,j,r)	Expenditure on intermediate goods, imported market prices
viga	(i,r)	Value of imported goods government consumption at agent prices
vigm	(i,r)	Government expenditure on imported goods
vims	(i,r,s)	Value of imported goods at market prices
vipa	(i,r)	Value of imported goods for household cons at agent prices
vipm	(i,r)	Value of imported goods for household cons at market prices
viws	(i,r,s)	Value of imported goods at world prices
vkb	(r)	Depreciation rate
vom	(pg,cott)	Variable O&M , in €/MWh
vst	(i,r)	Value of international transport sales (aggregated)
vtwr	(i,j,r,s)	Value of international transport sales
vxmd	(i,r,s)	Value of exported good from region r to region s
vxwd	(i,r,s)	Value of bilateral trade at world prices
weight_market		Weight in objective of cost structure constraint
weight_productiopn		Weight in objective of cost structure constraint
weighten		Weight in objective of energy cost structure constraint
weightka	(bubr,cott)	Weight in objective of capital cost structure constraint
weightla		Weight in objective of labour cost structure constraint
weightma		Weight in objective of materials cost structure constraint
xtrv	(j,r,s)	Trade taxes
yhr		Hours in a year (8760)