Introducing electricity load level detail into a CGE model – Part I – The calibration methodology

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Abstract

The growing importance of the electricity sector in many economies, and of energy and environmental policies, requires a detailed consideration of these sectors and policies in computable general equilibrium (CGE) models, including both technological and temporal aspects. This paper presents the first attempt to our knowledge at building temporal disaggregation into a CGE model, while keeping technological detail. This contribution is coupled with some methodological improvements over existing technology-rich CGE models. The model is able to account for the indirect effects characteristic of CGE models while also mimicking the detailed behavior of the electricity operation and investment present before only in bottom-up detailed models. The present paper is part I out of II and focuses on the bottom-up top-down calibration methodology needed to build such a model. Part II will present the CGE model formulated applied to the evaluation of an energy policy with temporal consequences.

Keywords: Computable General Equilibrium (CGE), Calibration.

JEL Codes: C68, D58, Q4, Q51, L60.

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1 Introduction

The last years have seen a huge effort in improving the representation of the energy sector in computable general equilibrium (CGE) models. The major motivation for this effort lies in the limitations of CGE when dealing with energy and environmental policies, in which the energy sector may play a relevant role: these policies may change the way technologies or fuels are used, and these changes may have broader economic consequences which need to be accounted for.

However, the detail of representation of the electricity sector has not been very large, and has been focused mostly on introducing technological detail (McFarland & Reilly, 2004, Paltsev et al., 2005 and Sue Wing, 2008) or feeding the CGE model with a BU-determined electricity behavior (Böhringer & Rutherford, 2008). This may be explained in part by the rabbit-and-elephant analogy introduced by Hogan and Manne (1977) and reminded by Ghersi and Hourcade (2006): the role of the energy sector in the economy is small, and even smaller the one of the electricity part of it. However, this analogy will probably not remain valid for a long time, at least for the contribution of electricity to the energy sector: we are already experiencing an increased electrification of the energy sector, and this will only grow in the medium term with the introduction of electric vehicles. Then, probably the rabbit will become an elephant, and the shortcomings of CGE models regarding the representation of the electricity sector will become more acute.

Indeed, the case of electric vehicles is a nice example of why there may be more reasons to introduce more detail in the representation of electricity supply and demand: the largest effect of these vehicles will not be in the amount of electricity produced, but rather, in the moment in which it is produced and consumed. The same happens with the expected impact of the demand-response programs currently being promoted associated with the smart meter rollout in many countries. And this change in the time in which electricity is produced or consumed is more relevant than it seems. Because of the non-storability of electricity, we might argue that electricity is not a single good: instead, it may be considered a different good depending on the time of the day it is produced or consumed. And, as such, it has different prices in different time periods. These differences in prices may be very relevant: in liberalized electricity markets (such as most of the European ones, but also in the US or other countries), the prices paid for electricity are not averages, but marginal ones. The change in the moment when electricity is used will change these marginal prices, and these are the prices that will be sent to the rest of the economy, not the average ones (which may not change) used by the typical CGE model. Introducing technological detail does not solve this problem.

Therefore, if we want to accurately represent the impact of energy or environmental policies on electricity prices, and of these prices in the rest of the economy, we need to consider an additional level of detail: time period detail, or, in power systems' jargon, load level detail. This is even more important for policies that modify the moment of time in which electricity is consumed.

The objective of this work is hence to present a CGE model in which both technology and load level detail are introduced for the electricity sector. A companion paper (part II) will present and apply it to the evaluation of the abovementioned policies, in this case a demand-response program in Spain.

Two main questions arise from this objective: How to include electricity bottom-up power sector detail into a CGE Top-down data structure and what are the advantages of addressing a policy analysis using the electricity detailed CGE model? This paper answer the first question by introducing a novel methodology, based on microeconomic and technological parameters for calibrating the electric power sector on a Social Accountability Matrix (SAM) scheme.

The paper is structured as follows. Sections two and three describe the methodology and the model used for introducing technology and load level detail into the CGE model. Section four presents the results of the calibration methodology and compares them to previous approaches. Finally, we offer some conclusions and thoughts about further research on this area.

2 Conceptual framework

CGE models represent economic activities as yearly aggregated commodities, which are produced at the efficient frontier of specific production functions by the combination of diverse production factors and supplementary commodities. The functional parameters that determine these production functions (elasticities and technological parameters) are estimated from real world behavior.

The commodity "electricity" at a specific point in time is a homogeneous product. However, its production portfolio is composed by several and very dissimilar production techniques. Therefore a single production function, such as the ones used in seminal CGE modeling like Hertel & Horridge (1997), Robinson et al. (1999) and Löfgren et al. (2002) are not enough to represent correctly the electricity sector.

Accordingly, several researchers have sought to achieve a higher degree of technological disaggregation or fuel supplier sectors representation in the electricity sector under the CGE modeling approach. Most of the largely adopted E3 assessment models like OECD-Green (J. Burniaux & Nicoletti, 1992), GTAP-E (J.-M. Burniaux & Truong, 2002) and MIT-EPPA (McFarland & Reilly, 2004 and Paltsev et al., 2005) underwent an continuous update process to better reflect the energy sectors dynamics. Nested energy production functions began to be used to reflect different fuel usage or different production technologies in the electricity sector.

However, such CGE extensions disregarded a crucial feature of electricity markets: their time dimension. Even if electricity is a homogeneous product at a specific moment in time, it becomes a heterogeneous commodity when considering different moments in time. This results from the fact that the electricity produced at a certain moment in time cannot be consumed at another period due to the impracticability[3] of storing it. As a consequence, technological disaggregation alone is not capable of representing correctly the electricity sector behavior. Most of the recent policy evaluations related with the electricity production and consumption behavior also disregard the time heterogeneity of electricity in their CGE formulation. Some recent examples are: Löschel & Otto (2009) that study the role of carbon capture and storage (CCS) uncertainty in emission reduction policies; Fæhn et al. (2009) that evaluate the consequences of carbon permit systems to unemployment in Spain; Turner & Hanley (2011) that investigate the environmental Kuznets curve under technological change; Bye & Jacobsen (2011) that look at welfare consequences of R&D and carbon taxes iterations; or Beckman et al. (2011) about the validation of GTAP-E parameters against historical

[3] Currently available technologies (batteries, heat and inertial storage, pumping, water management, etc.) present prohibitive costs for storage.

numbers. Rausch et al. (2011) represented an important advance in the representation of meaningful features in the evaluation of carbon pricing distributional effects in the U.S., like regional and income groups disaggregation, but time disaggregation was not taken into account in the CGE definition.

Some CGE models tried to overcome this limitation by taking into account in their technology disaggregation different technology portfolios characterized by their capacity factor and time of use. McFarland and Herzog (2006) is one example that makes use of this information to divide baseload technologies (typically coal and nuclear power plants), intermediate load capacity (natural gas combined cycle plants) and peaking capacity (simple cycle gas turbines) in order to assess the incorporation of carbon capture and storage in an integrated assessment.

However, including different time-dependable electricity technologies under the same nested production function, i.e., making use of different production functions for the same technologies under peak and off-peak demand periods, despite enriching the technology description, does not represent a real implementation of the heterogeneity in time of the electricity commodity.

Representing electricity production within a single nested structure implies the existence of a single electricity commodity, which presents average costs, prices and quantities. However, the information contained in average prices is not able to truthfully reflect the actual behavior of electricity prices in competitive, marginal-price electricity markets. In these markets, the electricity generation price corresponds to the bid of the marginal unit - the last power plant required to be dispatched at each time period -, and has no direct relation with average prices.

Therefore, there is no guarantee that an increase in the electricity demand would present an additional cost in the neighborhood of the average cost reflected in the national accounts. Actually, even the direction of the effect in prices is uncertain without further information. For example, an increase in the electricity demand in hours of lower demand (off-peak periods) would present a cost lower than the average price of electricity, since the additional energy needed to be produced could make use of cheaper variable cost power plants. As a consequence, the increase in demand would actually decrease the average price of electricity. Meanwhile, the opposite effect would occur if the increase in demand happens in peak hours, because costs incurred by the need of using more expensive variable cost units of production to serve the new demand would be greater than the initial average electricity price.

It is then evident that, in any policy evaluation where electricity demand shifts or reductions are considered, it is important to regard electricity as a heterogeneous commodity. This can only be done if we consider different electricity products for different time periods.

The difficulty to represent such detail inside a pure CGE model has led many researchers to adopt a partial top-down (TD) solution by making use of auxiliary bottom-up (BU) electricity models. Under this approach, the CGE model is fed exogenously by a bottom-up model that simulates the behavior of the electricity sector (Rutherford & Montgomery (1997) and Lanz & Rausch (2011)).

The use of a BU model to simulate electricity production adds flexibility to the representation of the specificities of electricity production technologies. However, the lack of electricity detail in the TD CGE model limits the information shared between these models to average values. Load block prices and quantities disparities, and their consequences for the general equilibrium income effects, consumer decisions, commodities substitutions and production costs are overlooked by such models and could limit their capability of evaluating economy-wide market interactions derived from energy policies.

This two-part document aims to present an answer to this problem. As we will see, it is possible to develop a pure CGE formulation suited to such complex policy assessments by incorporating at the same time the technological and the load level detail at the electricity demand and production levels.

Some key points must be addressed by such a model. Firstly, the resulting CGE model must present as many differentiated electricity commodities as the number of different technological portfolios used to provide electricity at the different demand levels. Secondly, the technology portfolio used at each load block must maintain the correspondence with the physical production characteristics of each production technology (thermodynamic efficiency, fuel use, self-consumption, availability, maintenance costs, specific subsidies, etc.). Thirdly, all costs that are not load-block-specific must maintain compatibility with their respective load block use of each technology (amortization of fixed costs, non-variable costs, start-up and ramp costs, market imperfection rents, etc.). Moreover, all the income created by the demand profiles of the different economic agents must be exactly equal to the variable and fixed production costs and the market power rents pertaining to each load block. The last requirement is necessary in order to maintain the model compatibility with the market clearing and zero profit conditions embedded in the Social Accountability Matrix (SAM) scheme.

As can be inferred from the points highlighted above, the introduction of technology and load level detail into CGE models faces several of the obstacles faced by the more comprehensive problem of convergence between BU and TD approaches.

Some papers already proposed a calibration procedure for making compatible both models in terms of data under a technology-only disaggregation scheme. Ian Sue Wing (2008) implemented a calibration procedure which consisted in disaggregating the SAM economic data into different electricity producing technologies by approximating the production factors and intermediate input expenditures according to expenditure shares obtained from real technological data, such as thermodynamic efficiency, labor use and construction capital requirements. Under this alternative the calibration problem is defined as the minimization of the deviations between the calibrated share of expenditures in intermediate inputs and production factors vs. the shares calculated from the benchmark bottom-up information.

The use of expenditure shares in calibrating the SAM aggregate presents some problems. The first and more essential one is the loss of the linkage between the original technological parameters, which determine the initial shares, and the resulting aggregate expenditures. Under this approach it is very difficult to incorporate changes in the original technological parameters without making additional exogenous assumptions or calibrating the SAM again. Therefore, this calibration solution is more appropriate to evaluate policies where technological changes are not critical.

Another limitation to the shares approach is the case when the determination of the expenditure shares does not take into account exhaustively the real market costs. In this case, an inconsistency between the national accounts and the original technological data would be evenly distributed between all costs sources. This feature helps achieve faster calibrated results; however it can also mask the presence of non-accounted costs or the existence of meaningful differences in the accounting data schemes of BU and TD data not taken into account during the calibration procedure.

The direct calibration of the technological parameters, instead of the use of shares, can overcome both limitations cited above. Under this alternative the calibration problem is defined as the direct minimization of the deviations between the calibrated technological parameters and the original data. Additional equations are used to derive arithmetically the social accountability aggregates departing from the calibrated microeconomic information. If technological changes matter, as for the case e.g. of substantial learning by doing effects, we can directly change the technological parameters in order to achieve the new macroeconomic figures. If an important cost source is overlooked in the problem definition, the macroeconomic totals will present a very dissimilar result, or the technological parameter will present a large deviation level, thus allowing easily identifying the problem. The trade-off of using this approach lies in the fact that convergence is more difficult to achieve because of the need to calibrate a larger number of variables (one calibrated variable for each technological parameter considered) and additional equations are needed to obtain the macroeconomic (micro-founded) totals and to enforce the SAM accountability equilibrium.

The choice of the mathematical formulation also influences the results obtained. Most of the literature related with this kind of calibrations, including Wing's work, makes use of quadratic objective functions for minimizing the errors between the original and the calibrated values. Although these functions allow for fast convergence, they can also result in a concentration of deviations in critical parameters (such as thermodynamic efficiency), which could in turn change the merit order of the efficient electricity operation decision.

The explicit representation of the technological parameters allows for easily adding additional calibration restrictions that require keeping the cost merit order unchanged after the calibration process. Another alternative to improve the mathematical formulation is to use a goal programming approach. This option, adopted in this paper and described in section 3.2, is capable of overcoming the calibration concentration limitation, and additionally, it has a completely linear formulation that can be presented as an advantage in comparison with the previously mentioned quadratic approach due to faster solver times and simpler global optimal solution assurance.

All this said the objective of this paper is to present a SAM calibration method suited to include several attributes that until now were only present in bottom-up electricity models. This calibration method is the first step to be able to develop a CGE model perfectly capable of address complex electricity issues as it will be show in the part II paper of this work (Rodrigues and Linares, 2013). The developed SAM and CGE model will present simultaneously location, technological and time disaggregation in the electricity activities; macroeconomic aggregates directly obtained from technological micro-foundations; and a goal-programming calibration procedure capable of achieving a TD representation perfectly compatible with BU technological parameters.

3 Analytical framework

3.1 Model Overview

As previously mentioned, the goal of this paper is to develop a consistent formulation to incorporate location, load level and technology detail into TD CGE models.

In data terms this requires adding to a SAM not only a column disaggregation, characteristic of the disaggregation of electricity production technologies, but also a row disaggregation necessary to include the load level and the location zonal nodes detail in either the demand profile of economic agents and the available production portfolios of generation technologies.

Figure 1 shows the electricity related expenditures in a schematic SAM representing the economy flow of uses and resources to be represented in a typical general equilibrium model[4].

[4] From now on this work adopts a nomenclature were smaller lower caps letters with a bar above represent the parameter considered, while capital letters represent the variables of the calibration model.

Figure 1. Schematic social accountability matrix.

		Production/Uses						
		Q	Electricity	Factors	Taxes	Institutions	Savings-Investments	Exports
Products/ Resources	Q		$\overline{e\_\imath\imath}_g^{elet}$	-	-		-	
	Electricity	$\overline{e\_\imath\imath}_s^{elet}$	$\overline{e\_\imath\imath}^{elet,elet}$	-	-	$\overline{\mathrm{e\_\imath nst}}^{\mathrm{elet}}$	-	$\overline{\mathrm{e\_ex}}^{\mathrm{elet}}$
	Factors		$\overline{e\_pf}_{pf}^{elet}$	-	-	-	-	-
	Taxes		$\overline{e\_tax}_{tx}^{elet}$	-	-			
	Institutions	-	$\overline{e\_allow}^{elet}$				-	
	Savings-Investments	-	-	-	-		-	
	Imports		$\overline{e\_m}^{elet}$	-	-			-

Q = non electricity productive sectors. Parameters are described in detail in Annex I. Source: Own elaboration.

The desired electricity detailed SAM must be able to reproduce the exact figures present at the original Figure 1 SAM, while being able to represent additional information about the different electricity activities - GEN (Generation) and TD&O (Transmission, Distribution and Other activities) - and their heterogeneity in time and location. A schematic representation of the extended SAM with this information can be seen in Figure 2.

Analyzing the electricity resources represented at the extended SAM (the electricity row in Figure 2) it can be seen that the final electricity product is divided into two different products roughly representing the energy and the power components of the electricity activity. Due to the presence of congestions, network constraints, different regulation schemes and different market structures in the national borders, these products are differentiated by location (location 1,.. location n). Additionally, and mostly important for the electricity generation behavior, the electricity products are further disaggregated by their time of consumption (periods and load blocks) [5,6].

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[5] The electricity heterogeneity in time is also present at the access tariffs of distribution activities. Different power tariffs are charged to different load profile consumers to reflect the congestion and other network restrictions of peak use hours.

[6] From now on we choose to focus this paper methodology on explaining the introduction of generation activity detail on CGE models. This option is made to avoid the excessive length needed for addressing the TD&O activity in detail. However, introducing time heterogeneity for the contracted electricity power and different costs representation for the TD&O activity would follow a similar approach as the introduction of energy disaggregation into load blocks, load levels and different generation technologies.

Figure 2. Schematic social accountability matrix with electricity detail represented.

	Q	Electricity										Factors	Taxes	Institutions	Savings-Investments	Exports
Activity		TDeO	GEN													
Location			Loc.1	Location n												
Period			…	Winter	Summer											
Load block			…	…	lb1	lb n										
Technology			…	…	…	Tech 1		Tec. t		Imports	Market Failures and non-accounted costs					
Cost type			…	…	…	Variable cost	Fixed cost	V	F							
Q		E_II_QE_TDeO Production inputs	…	…	…	VAR_E_II_QE_GEN Fuel cost + VOM	FIX_E_II_QE_GEN FOM	…	…	-	-	-	-		-	
Electricity – energy – Location 1 – Summer – ll.1	E_II_EQ_ENERGY Energy only bill	E_II_EE_TDeO Network Losses	…	…	…	E_II_EE_GEN Electricity own consumption + Pumping consumption	-	…	-	-	-	-	-	E_I_ENERGY Energy only bill	-	E_EX_ENERGY Energy only bill
Electricity – energy – Location 1 – Summer – ll.n			…	…	…		-	…	-	-	-	-	-		-	
Electricity – energy – Location 1 – Wint – …	…	…	…	…	…		-	…	-	-	-	-	-	…	-	…
Electricity – energy – Location n – ⋮ – …	…		…	…	…	…	-	…	-	-	-	-	-	…	-	…
Electricity – power	E_II_EQ_POWER Power bill	…	-	-	-	-	-	-	-	-	-	-	-	E_I_POWER Power bill	-	E_EX_POWER Power bill
Factor		E_F_E_TDeO Labor and Capital	…	…	…	-	E_F_E_GEN Labor FOM and Capital amortization	-	…	-	TOTAL_SURPLUS Market Failures and non-accounted costs	-	-	-	-	-
Taxes		E_TAX_E_TDeO Taxes	…	…	…	E_TAX_E_GEN Product, production taxes and CO2 payments	E_TAX_E_GEN Social Contributions FOM	…	…	-	-	-	-			
Institutions	-	- -				-			-		-				-	
Savings-Investments	-	- -				-			-		-	-	-		-	
Imports		-	…	…	…	-	-	-	-	E_M_E_GEN Imports	-	-	-			-

Energy only bill = energy-only electricity payments; Power bill = network + commercialization electricity payments; load block (lb); load level (ll); Variable operation and maintenance costs (VOM); Fixed operation and maintenance costs (FOM). Source: Own elaboration.

As in any SAM scheme, the double-entry accounting and the square matrix definition are respected in our electricity detailed data framework. Therefore, any row disaggregation is reflected by additional columns of the electricity production activity and the namesake corresponding rows and columns sum the same total expenditure amounts.

Nevertheless, additional information about the physical production characteristics can be represented in the same accounting scheme without sacrificing any of its properties. By this token, the electricity activity column disaggregation includes additional information about the technologies used for producing electricity.

Each location and time period has its own differentiated production structure in the electricity generation activity. This is necessary to reflect the different technology portfolios used at different time periods and, most importantly, the change in the production behavior of the same generation technology with time. This happens because the same electricity production technology can act differently according to different demand and price levels. The clearest example of this behavior is given by the generation units capable of storage (pumping units for example) that act as demanders on lower price periods and suppliers at higher prices periods. This differentiated behavior in time could also be promoted by specific technological characteristics of the unit cycling behavior, spinning reserve requirements, ramp constraints, production intermittence and other technical characteristics when comparing peak and off peak load periods.

Two additional columns are considered in the electricity production description. The first one represents the electricity imports that take place at each location and time period. The second additional column is used to represent any non-explicitly accounted electricity production costs, the presence of extraordinary market rents and the necessary monetary transfers between load blocks in order to pay for fixed costs.

Dealing with such disaggregation level of the electricity activity added to the representation of fixed costs and market imperfections is not an easy task in a social accountability approach. The next sections of this paper focus on explaining the modeling challenges of this framework and to propose a solution for achieving the aimed convergence between the CGE TD and the electricity BU formulations in data terms[7].

3.2 The reconciliation between BU and TD modeling: The calibration procedure

Most of the difficulties for building the electricity detailed TD data framework lie in the incorporation of bottom-up technological and demand data into the macroeconomic SAM framework.

It would be a trivial process to transform engineering costs information into demand for production factors and intermediate inputs under a perfectly compatible accountability approach. The additional SAM rows and columns disaggregation would be achieved by simple arithmetic manipulations. However, in the 'real world', the different costs structures, diverse data sources (company accountability vs. technical characteristics) and distinct data availability difficult this process.

One way to achieve a suitable process to make compatible the engineering and economic costs representation is allowing a certain degree of freedom to the different expenditure components of the electricity activity.

The calibration process proposed in this work for achieving this objective consists of three groups of equations. The first group relates the chosen calibration variables with their upper and lower deviations from the original data. The second equations group maintains the equivalence between the original and the extended SAM figures. They are simple sum constraints that preserve the original benchmark year data, described in Figure 1, as a sum of the disaggregated values of the electricity extended SAM, described in Figure 2. The last group of equations represents the real linkage between the BU microeconomic data and the TD macroeconomic figures. It includes equations that arithmetically obtain each of the SAM macroeconomic aggregated values directly from the electricity demand and technological BU information.

[7] In part II of this paper (Rodrigues & Linares, 2013) we present the formulation of a CGE model that incorporates the detailed treatment of the electricity activity in its design and tries to answer the question of how much it is worth in an electricity policy assessment to add such level of detail for the general equilibrium model.

Once these equations groups are defined we can determine a mathematical problem that minimizes the deviations of the benchmarked BU technologic parameters while respecting the macroeconomic expenditure constraints and the SAM equilibrium assumptions.

The structure chosen for approximating the BU values to the aggregated TD expenditure information applied in this work takes the form of a Chebyshev or minimax goal programming approximation (Romero, 1991). The full calibration model is described in Annex I and the general problem structure is presented below:

Min:

$$\sum_{c} \mathrm{MAXIMUM\_DEVIATION}_{i} \qquad 3.2\text{-}1$$

Subject to:

First Group: Chebyshev deviation equations:

$$\mathrm{X_c} - \bar{\mathrm{q}}_c + \mathrm{N}_c - \mathrm{P}_c = 0 \qquad , \forall \mathrm{c} \qquad 3.2\text{-}2$$

$$\frac{\mathrm{N_c}}{\bar{\mathrm{k}}_\mathrm{c}} + \frac{\mathrm{P_c}}{\bar{\mathrm{k}}_\mathrm{c}} \leq \mathrm{MAXIMUM\_DEVIATION}_c \qquad , \forall \mathrm{c} \qquad 3.2\text{-}3$$

$$\mathrm{N_c}, \mathrm{P_c} \geq 0 \qquad , \forall \mathrm{c} \qquad 3.2\text{-}4$$

Second Group: SAM 'Must follow' accountability constraints:

$$\overline{\mathrm{sam}}_{\mathrm{row1,column1}} = \sum_{(row_2, column_2) \in (row_1, column_1)} \mathrm{EXTENDED\_SAM}_{row_2, column_2} \quad \forall\, row_1, column_1 \qquad 3.2\text{-}5$$

Third Group: Micro-founded macroeconomic aggregates:

$$\begin{aligned} &\mathrm{EXTENDED\_SAM}_{row_2, column_2} \\ &= Variable\ Costs(\mathrm{X}_1, \dots, X_c) + Fixed\ Costs(\mathrm{X}_1, \dots, X_c) \\ &+ Non\ accounted\ costs\ and\ market\ imperfections \end{aligned} \qquad 3.2\text{-}6$$

Where $\mathrm{X_c}$ are the technological parameter decision variables; $\overline{\mathrm{q_c}}$ are the desirable values of $\mathrm{X_c}$ (i.e. the benchmark technological parameter values); $\mathrm{N_c}$ are the negative deviation variables; P_c are the positive deviation variables; $\bar{k}_c$ are the deviation normalizations associated with the cth goal; $\overline{sam}_{row1,column1}$ are the SAM benchmark data (Figure 1 cells); $EXTENDED\_SAM_{row2,column2}$ are the SAM macroeconomic aggregates of Figure 2 resulting from the calibrated variables; and $Variable\ Costs(X_1, \dots, X_c)$ and $Fixed\ Costs(X_1, \dots, X_c)$ are the functions that translate the BU technological parameters into macroeconomic aggregates.

The goal programming formulation adopted is able to overcome the concentration of deviations previously described in section 2 and, if added to the must-follow accountability constraints necessary to maintain the SAM equilibrium, can determine the calibration procedure necessary to match the electricity BU and TD data and achieve the requirements to define the General Equilibrium Model with Electricity Detail (GEMED) presented at part II of this work (Rodrigues and Linares, 2013).

Representing the macroeconomic aggregates in terms of the technological parameters provides a very important additional advantage to this calibration process. Additional constraints can be easily added to the calibration process to avoid any unreal, exaggerated or undesirable calibration results. With this intent an additional merit order condition is added to the calibration model in order to avoid unreal calibrated results.

In order to ensure the existence of a solution it is necessary that every cell of the newly extended SAM is related with at least one of the parameters to be calibrated. Twelve technological and monetary parameters (x_i) were chosen for this intent in the calibration process: the thermodynamic efficiency, overnight construction costs, variable operation and maintenance costs in equipment, fixed operation and maintenance costs in equipment, CO2 equivalent content by fuel, electricity self-consumption, labor and social contribution costs, network losses, imports prices adjustments and exports prices adjustments.

Defining the first and second group of equations follows a clear and unchanged mathematical structure, however it is in the third group of equations that lie most of the assumptions needed to determine the electricity detailed social accountability framework. The next subsections will identify the challenges and the assumptions adopted in order to obtain the macro aggregates departing from microeconomic information, translating variable costs, fixed costs and market imperfections into the proposed extended SAM structure.

3.2.1 Accounting for fixed costs and market imperfections in the SAM framework

Different costs can have different temporal amortization structures. Some costs are directly related to the amount produced (the very definition of variable costs). These costs are easily represented on a load block disaggregated scheme.

Equations relating fuel, taxes, maintenance, and any other variable costs can be directly associated with the corresponding location and time disaggregated cell of the electricity extended SAM. Take for example the generation production fuel costs. They are a function of the technology thermodynamic efficiency ($\eta_{y,l,t}$), the fuel price ($\bar{p}^{fuel}_{y,p,t,f}$), the power generated by the technology at the each specific location and load block ($\overline{pgen}_{y,t,f,l,gp,gb}$) and the duration of the load block (The detailed equations for all micro-macro expenditure relations are presented in Annex I).

$$\text{VAR\_E\_II\_QE\_GEN}_{y,gne=f,l,p,b,t} = \left(\sum_{f} \eta_{y,t,f}\, \bar{p}^{fuel}_{y,t,f}\overline{pgen}_{y,t,f,l,p,b}\right)\overline{dur}_{l,p,b} \qquad 3.2\text{-}7$$

As can be seen in equation 3.2-7, the microeconomic parameters necessary to obtain the total fuel costs are already time and location dependent. Therefore, if we are able to obtain data about the electricity market behavior for our benchmark year (electricity demand, generation technology production and fuel prices), disaggregating the variable costs in the SAM structure is just a matter of solving arithmetically the above equation for each time period column.

Other costs however can be problematic to represent in a load block disaggregated scheme: the amortization of fixed costs (including those resulting from excess capacity), the observed markups in non-competitive markets, or any other rents derived from market imperfections.

Take for example the amortization of the power plants installed capacity. Fixed investment costs are usually paid under an annual amortization schedule. But the income used to pay such amortization in power systems usually comes from marginal prices, as described by Pérez-Arriaga and Meseguer (1997).

The first problem that we face is how to determine the amount of fixed costs paid by the electricity generating companies in each year. While the total capital payments for the calibration year can be obtained from the company accounts, some ad hoc assumptions need to be made to determine the contribution of each technology to the total amount of investment costs and the proportion of fixed costs paid in each of the years to come.

There is not a "right" or "perfect" way to make these assumptions. Nevertheless, for the case of the electricity sector the close relationship between the large amounts of money required for the construction of electricity infrastructure and the strong use of bank loans and financial instruments allows us to consider a well-defined amortization schedule.

We choose to consider the amortization payment of old and new production capacity as an annuity paid during the operation lifetime of the power plant[8]. The total cost to be amortized at the beginning of the power plant lifetime is the overnight cost, which includes interests paid during construction if required.

Even after defining the annual amortization schedule, the actual money available for paying the electricity fixed costs is income dependent and the company's income is load block dependent: a second problem emerges.

In marginal-settling electricity markets, like the Spanish case, the market price should be equal to the marginal unit bid necessary for supplying total demand. The sector income differs highly between load levels. Therefore, for every non-marginal unit, peak demand periods contribute substantially more to the payment of fixed costs than off-peak periods. Moreover, each technology receives only the amount proportional to its utilization in the load block production level.

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[8] A bottom-up model usually disregards any impact of previous installed capacity in the costs accountability because their levels do not modify the partial equilibrium future optimal decisions, as they represent sunk costs. However, in a general equilibrium approach the composition of such previous capacity can represent the future solvency of a certain technology; besides it also represents indirect capital effects that should be accounted for the correct evaluation of certain policy assessments.

How much of each load block's income contributes to the payment of the total investment costs and which are the other destinations of the remaining income after paying variable costs?

In a perfectly competitive market and under an exhaustive representation of the activity costs, the sum of the total surplus obtained at each load block after deducting the variable cost payments should correspond exactly to the capital requirements for paying off the corresponding power plant capacity (and any other additional fixed costs). Any divergence from this outcome would result in an arbitrage opportunity in the market, meaning an entry signal to potential competitors and/or the bankruptcy of existing firms.

But neither the exhaustive representation of costs nor a perfect competitive market are the usual cases for the electricity sector structure or for its representation in models. Regarding costs, the complexity and dimensionality issues make impossible to represent the unit commitment detail in an expansion planning model, and vice versa. Moreover, the electricity sector features typically a series of additional market imperfections, market power rents and windfall profits characteristic of each scenario and market structure.

Therefore, the translation of the bottom-up electricity behavior into a TD modeling approach must face at the same time an imperfect competition environment with an undefined proportion of costs paid by load blocks.

Let's start with the second issue: the load block distribution of non-load block specific costs. We assume that all non-variable costs are divided between load blocks according to the proportion of the load block surplus after deducing the specific variable costs pertaining to it (equation 3.2-8 and 3.2-9). This representation is perfectly compatible with the direct consequences of a perfectly competitive market environment but can be also applied to our imperfectly competitive electricity market.

$$\text{Load Block Surplus}_{y,l,p,b} = \text{Total Income by Load Block}_{y,l,p,b} - \sum_{t,f} \text{Variable Costs by Load Block}_{y,l,p,b,t,f} \qquad 3.2\text{-}8$$

$$\text{Fixed Costs Distribution Factor by Load Block}_{y,l,p,b} = \text{Load Block Surplus}_{y,l,p,b} \Big/ \textstyle\sum_{p,b} \text{Load Block Surplus}_{y,l,p,b} \qquad 3.2\text{-}9$$

Now comes the question of how to represent imperfect competition in the TD model. There is not a single way of modeling imperfect competition, but in our case our choice is directed by the need to determine the amount of market imperfection rents acquired at each load block by electricity generators. Therefore, we assume all market imperfections approximated by the surplus obtained from subtracting the calibrated bottom-up sources of variable and allocated fixed costs from the observed load block incomes. This market imperfection rents information can be easily used to determine a mark-up price for each load block in a CGE model.

$$\begin{aligned}\text{Total Income by Load Block}_{y,l,p,b} &= \sum_{t,f} \text{Variable Costs by Load Block}_{y,l,p,b,t,f} \\ &+ \text{Distribution Factor}_{y,l,p,b} \sum_{t,f} \text{Fixed Costs}_{y,l,p,b,t,f} \qquad 3.2\text{-}10 \\ &+ \text{Mkt Failures and Non Accounted\_Costs}_{y,l,p,b}\end{aligned}$$

This way of representing fixed, variable and market imperfection rents has two consequences. First, all non-explicitly represented costs of the electricity sector are endogenously built-in in the determination of the load block market surplus. Second, there is no motive for the market surplus to be positive in all load blocks; actually, it is expected that lower demand load blocks present smaller market surplus amounts, due to their lower price levels, and that non optimal investment decisions may result in a negative surplus until over the years their amortization levels reduce their influence.

As can be seen, before being able to execute the proposed calibration procedure an intermediary step it necessary to determine the fixed costs amortization distribution between load blocks, the existent imperfect market rents at our benchmark data and the amount of costs not addressed by our microeconomic detailing of the electricity activity.

3.2.2 The trick: using a bottom-up model to define a top-down detailed model

The distribution of the costs not-load-block-specific could be determined by a heuristic or discretionary exogenous assumption. These alternatives however make it difficult to use the same framework for further extensions (such as developing an integrated hybrid BU and CGE model) as they are not necessarily correctly reflected in the BU component.

In order to avoid further incompatibilities, this work makes use of a bottom-up power generation expansion model, based on Linares et al. (2008), to define not only the cost distribution between load blocks but also each technology production decision, variable and fixed costs amounts, and load block market imperfection rents. The electricity expansion and operation model is used as a previous step to the calibration process in order to feed the information illustrated in the Figure 3.

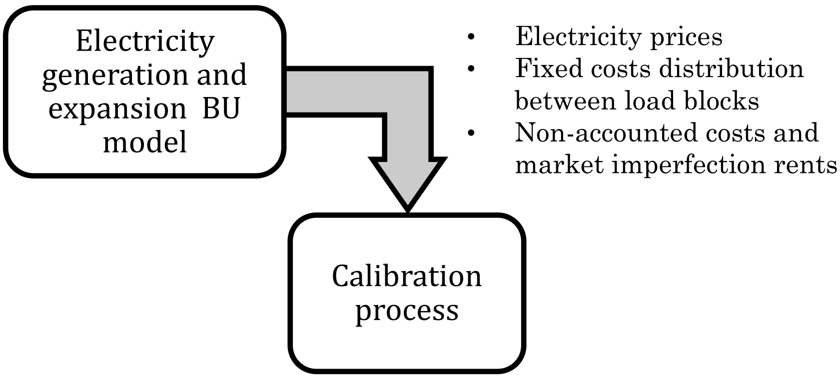

Figure 3. Bottom-up electricity model and calibration procedure linkage.

The marginal operation model aims to represent the electricity market competitive results by choosing the most inexpensive technologies to produce enough electricity to meet demand in the reference year. The variable costs for each load block and the fixed costs for the reference year operation are then identified by the model.

Subsequently, the modeled marginal unit cost is confronted with the observed real world prices in order to define the portion of income and costs not accounted for in the model formulation. Start-up and ramp costs, market imperfection rents and market power use that could be derived from the oligopolistic structure of the market are examples of terms not addressed in the BU model chosen in this work. Even so, one cannot deny the possible presence of these terms in the determination of real world prices, and therefore their consequent presence in the accounting frameworks that define the CGE data.

The resulting modeled prices, added to the adjustment of the costs accounted for in the real world, can be used to obtain the total generation remuneration. The fixed costs are allocated at each load block according to the surplus of this remuneration after deducting the model variable costs.

After excluding the variable and fixed costs, the remaining money represents all economic flows not explicitly described in our BU model. These flows are allocated to remunerate all market imperfections and the non-accounted costs, and they are treated as capital terms in the CGE model[9].

With all assumptions identified and all group of equations completed defined we can finally put the calibration process to a test and evaluate its results. As mentioned earlier, for more details on the calibration model all equations, parameters and variables are described in Annex I.

4 Results

The calibrations performed consider different load blocks aggregations in order to compare the additional calibration complexity required for a time differentiated SAM framework when compared with a traditional SAM calibration. Table 1 describes the simulation scenarios assumed in our research.

[9] Generation cycling costs (start-up, ramp and shutdown costs) can be also considered as additional fuel costs or they can be internalized by the calibration process in representing 'lower' average thermodynamic efficiency of power plants technologies involved in numerous cycling behavior.

Table 1. Simulation scenarios.

Scenario name	Number of load blocks	Description
LB_1	1	Typical SAM with one electricity product.
LB_6	6	1 season; 2 day types (working and holiday); 3 hour types (off-peak, medium and peak hours).
LB_20	20	1 season; 2 day types (working and holiday); 10 hour types.
LB_45	45	5 seasons (winter1, spring, summer, autumn and winter2); 3 day types (working 1: Monday and Friday; working 2: Tuesday, Wednesday and Thursday; and holidays); 5 hour types (off-peak , medium, peak).
LB_90	90	5 chronologic seasons (winter1, spring, summer, autumn and winter2); 6 day types (5 working days and 1 holiday); 3 hour types (off-peak, medium, peak).
LB_180	180	12 chronologic months; 3 day types (working 1: Monday and Friday; working 2: Tuesday, Wednesday and Thursday; and holidays); 5 hour types (super off-peak, off-peak, medium, peak, super peak).

Source: own elaboration.

Two different calibration strategies are used: the minimax one proposed in the paper, and the quadratic form usually proposed in the literature. As underlined in the previous section, the main undesirable consequence of the calibration of parameters for the electricity sector operation is the possibility of changing the original cost merit order of the production technologies. Therefore our analysis focused in evaluating the levels of maximum deviated parameters, besides the more usual average error assessment.

The quadratic method under the scenario LB_1 is used to compare our paper's formulation with another published calibration method described in Sue Wing's work (2008). However, due to very dissimilar data sets (Spanish vs. United States data) and different use of parameters in the calibration process (technological parameters vs. aggregated shares) we can only say that the method presented by our paper achieved a superior but similar level of magnitude in the calibrated parameters errors when compared to Sue Wing's work.

The results obtained by the SAM calibration model, necessary to define the GEMED model formulated at the second part of this work (Rodrigues and Linares, 2013), are presented in **¡Error! No se encuentra el origen de la referencia.**.

Table 2. Parameter with maximum deviation after the calibration process.

	MinMax (%)	Quadratic (%)	Variable with max deviation
LB_1	4,73%	8,59%	O&M equipment's fixed cost
LB_6	5,22%	9,48%	O&M equipment's fixed cost
LB_20	5,51%	10,00%	O&M equipment's fixed cost
LB_45	5,40%	9,80%	O&M equipment's fixed cost
LB_90	5,41%	9,81%	O&M equipment's fixed cost
LB_180	5,58%	10,12%	O&M equipment's fixed cost

Source: own elaboration.

Focusing on the analysis of the maximum deviated parameter, the operation and maintenance equipment fixed costs (O&M_FOM_EQUIP) faced by the electricity generation technologies was the parameter which required the larger adjustment of the original data, an 4,73% deviation under the LB_1 scenario when compared to the benchmark data. This is indeed an encouraging outcome if compared with the 10-20% range of the majority of deviations estimated in the Sue Wing work, and mostly especially when compared to the 43.2% maximum calibrated error (of steam turbine generation expenditures). Again, it is important to emphasize that this result does not prove that our calibration procedure is any better that Sue Wing's proposal, due to different data sets and different calibrated parameters.

Nonetheless, stronger conclusions can be drawn when comparing the quadratic formulation and the minimax alternative inder the same dataset. Observing again **¡Error! No se encuentra el origen de la referencia.** results we can show that the minimax model consistently bests the quadratic alternative in terms of maximum errors on the calibrated parameters. Moreover, it requires less computer memory resources and achieves faster solving times[10].

We therefore argue that there are clear advantages in using the Min Max calibration procedure described in this paper. However the great advantage of the paper proposed methodology is on the use of a microeconomic founded calibration of parameters as we will see in the sequence.

[10] Information about the execution time and memory requirements for each model is available upon author request.

Under a traditional SAM calibration procedure, the macroeconomic expenditure variables are directly calibrated to reproduce the benchmark year data. This method presents two strong limitations. The calibrated results lose their direct consequence relationship with the original bottom-up parameters. A policy assessment that requires changes on the technological parameter is much more difficult to achieve then in a micro-founded SAM matrix.

The second strong limitation is the fact that under the macroeconomic based calibration, it is very difficult to consider technology based constraints in the calibration process in order to avoid unreal results. The importance of the micro-foundation is illustrated by the results presented at Table 3.

Table 3. Variable cost merit order of original and calibrated technology parameters without bottom-up cost order enforcing constraints.

	Original		**LB_1**		**LB_6**		**LB_20**		**LB_45**		**LB_90**		**LB_180**	
	#	€/MWh	#	€/MWh	#	€/MWh	#	€/MWh	#	€/MWh	#	€/MWh	#	€/MWh
Wind	1	0,00	1	0,00	1	0,00	1	0,00	1	0,00	1	0,00	1	0,00
Hyd Res	2	1,78	2	1,78	2	1,78	2	1,78	2	1,78	2	1,78	2	1,78
Hyd RoR	3	1,78	2	1,78	2	1,78	2	1,78	2	1,78	2	1,78	2	1,78
ORSR	4	2,40	4	2,40	4	2,40	4	2,40	4	2,40	4	2,40	4	2,40
Nuclear	5	4,43	5	4,43	5	5,15	5	5,15	5	5,09	5	4,95	5	5,15
Imp. Coal	6	42,37	6	42,14	6	45,93	6	45,93	6	45,61	6	44,84	6	45,92
Nat. Coal	7	43,00	7	42,77	7	46,60	7	46,59	7	46,27	7	45,50	7	46,59
CCGT	8	46,75	8	46,65	**9**	**50,50**	**9**	**50,60**	**9**	**50,52**	**9**	**50,52**	**9**	**50,58**
NRSR	9	50,05	9	50,05	**8**	**49,87**	**8**	**49,86**	**8**	**49,88**	**8**	**49,88**	**8**	**49,86**
F-O Turb.	10	92,36	10	92,36	**11**	**105,70**	**11**	**105,69**	10	104,52	10	101,87	**11**	**105,69**
F-G Turb.	11	105,54	11	105,54	**10**	**105,17**	**10**	**105,16**	11	105,19	11	105,19	**10**	**105,16**

Source: own elaboration.

= variable cost merit order; Hyd Res = reservoir hydropower; Hyd RoR= run of river hydropower; ORSR = other renewables special regime (mostly solar); Imp. Coal = imported coal; Nat. Coal = national coal; CCGT = combined cycle gas turbine; NRSR= nonrenewable special regime (mostly gas cogeneration technologies); F-O and F-G Turb. = turbine with fuel oil or gas combustibles.

Table 3 presents the variable cost merit order of the electricity production technologies under the original bottom-up parameters and the calibrated parameters. As can be seen, the calibration model changes the technologies merit order for all but one load blocks aggregation evaluated. Mostly specially, the merit order changes concentrate at the most expensive peak technology units.

This is a strong undesirable result of the calibration model. The emission levels, combustibles used, technical restrictions between others of the merit order changed peak units are very much different. Any model built upon this calibrated data can present very strong biased and incorrect results.

This problem can be easily solved under a micro-founded calibration model as the one proposed in this work. The simple addition of a merit order enforcing constraint avoids initially cheaper technologies to become more expensive them their competitors. The results obtained on this work calibration model and the subsequent general equilibrium model (Rodrigues and Linares, 2013) take into account such additional merit order constraint to provide more realistic policy assessments results.

5 Conclusions

The increasing electrification of energy systems across the world, and the growing role of policies that change the way in which electricity is consumed, such as demand response programs or the introduction of electric vehicles, make it more necessary than ever a more detailed representation of the electricity sector in CGE models, so that, while retaining the assessment of indirect effects characteristic of CGE models, we may be able to account correctly for the effect of load shifts and technological changes.

This paper has presented the first attempt to our knowledge at building temporal disaggregation into a SAM accountability scheme, while keeping technological detail. This contribution is coupled with some methodological improvements over existing technology-rich CGE models data sets, in particular a minimax calibration procedure made it possible by the micro-founded representation of the electricity macroeconomic accounts.

Instead of the usual quadratic alternative we opted for a linear minimax calibration procedure. This allows avoiding the variable concentration of deviations, which is a desirable property to avoid unwanted cost merit order changes in the electricity market settlement. Moreover, as our results show, the minimax model consistently bests the quadratic alternative in terms of the maximum deviations obtained for the calibrated parameters on our data set.

Instead of the most common used shares on the macroeconomic aggregation figures we calibrate directly the technological parameters to reflect the macroeconomic data. This allows maintaining the linkage between the original technological parameters and the resulting aggregate expenditures when developing a CGE model. Consequently, the resulting model could easily handle endogenously technological evolution and learning-by-doing consequences which are more difficult to manage under a share calibration approach. Likewise, the technological representation also allows the introduction of additional constraints, like merit order, maximum production capacities, price variation ranges, and many other relevant physical limitations directly as constraints of the calibration model in order to obtain more realistic results.

Even so, in the authors' opinion the most important contribution of this paper is building for the first time temporal electricity generation disaggregation into a social accountability framework. This result is the first necessary step in order to develop a CGE model capable of reproducing correctly the electricity price behavior on competitive wholesale markets. This attribute is particularly important in policy assessments that include load shifting, demand profile changes and technology substitution, as we will see in the second part of this paper (Rodrigues and Linares, 2013).

Additionally, the compatibility between microeconomic and macroeconomic data sets achieved by this calibration process is a necessary requirement if one wants to develop a truly integrated hybrid model, which considers simultaneously the behavior described by the equations of a BU electricity expansion model and a TD CGE model into a single modeling framework.

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Annex I – The Calibration Model

Sets:

SAM	Sectors (s), institutions (i), taxes (tx), production factors (pf), investments, exports and imports
g (s)	All goods (sectors) of the economy, including the disaggregated electricity commodities
gne (sne)	Non electricity goods (sectors) and TD&O electricity activity
pf	Production factors (Labor and Capital)
tx	Taxes (production taxes, product tax and social contributions)
i	Institutions (households and government)
ey	Execution year of SAM and CGE model
y	Simulation years for electricity operations and investment model
l	Location
t	Technology (Nuc, NCoal, ICoal, CCGT, F-G, Hyd_Res, Hyd_RoR, Wind, ORSR, NRSR, Pump)
t_non_intt	Non intermittent technologies
f	Fuel (Enriched_Uranium, Coal, Natural_Gas, Fuel-oil)
p (dp,gp)	Period (season)
b (db,gb)	Load block
c	Set of bottom-up calibrated variables (listed below)

Variables:

Objective variables to be calibrated:

$\mathrm{OeM\_VOM}_{y,t}$	calibrated operation and maintenance variable costs (€/MWh)
$\mathrm{OeM\_FOM}^{labor}_{y,l,t}$	calibrated operation and maintenance labor fixed costs (€/KW)
$\mathrm{OeM\_FOM}^{sc}_{y,l,t}$	calibrated operation and maintenance social contribution fixed costs fixed costs (€/KW)
$\mathrm{OeM\_FOM}^{equip}_{y,l,t}$	calibrated operation and maintenance equipments fixed costs (€/KW)
$\eta_{y,l,t}$	calibrated thermodynamic efficiency (MWh/kg)
OWN_CONS	calibrated own consumption of electricity by the generation activity (%)
$\mathrm{OVERN\_COSTS}_{y,t}$	calibrated overnight new capacity investment costs (€/KW)
$\mathrm{LOSS}_{y,l,p,b}$	transmission and distributions losses proportion
$\mathrm{CO2e\_CONTENT}_{y,t,f}$	CO2e content in emissions of technology t using fuel f
$P\_IMP\_ADJ_{y,l.dp,db}$	Adjustment factor for observed imported electricity prices
$P\_EXP\_ADJ_{y,l.dp,db}$	Adjustment factor for observed exported electricity prices

Objective deviation variable to be minimized

$\mathrm{MAX\_PCTG\_DEV}_y^c$	Maximum percentage deviation of calibrated variables

Deviations of the calibrated variables:

$\mathrm{N\_DEV\_}*$	Group of negative deviations for each one of the objective variables described above
$\mathrm{P\_DEV\_}*$	Group of positive deviations for each one of the objective variables described above

Electricity extended SAM cell accounts:

$\mathrm{E\_II\_QE\_GEN}_{y,gne,l,gp,gb,t}$	Electricity generation intermediate input expenditure in non-electric goods for each location, season period, load block and production technology (Electricity extended SAM) (millions €)
$\mathrm{E\_II\_EE\_GEN}_{y,l,dp,db,gp,gb,t}$	Electricity generation intermediate input expenditure in a determined electricity load level for each location, season period, load block and production technology (Electricity extended SAM) (millions €)
$\mathrm{E\_F\_E\_GEN}_{y,pf,l,gp,gb,t}$	Electricity generation production factors expenditure for each location, season period, load block and production technology (Electricity extended SAM) (millions €)
$\mathrm{E\_TAX\_E\_GEN}_{y,tx,l,gp,gb,t}$	Electricity generation taxes expenditure for each location, season period, load block and production technology (Electricity extended SAM) (millions €)
$\mathrm{E\_M\_E\_GEN}_{y,l,gp,gb,t}$	Electricity generation imports expenditure for each location, season period, load block and production technology (Electricity extended SAM) (millions €)
$\mathrm{E\_II\_EQ\_ENERGY}_{y,sne,l,dp,db}$	Non electric sector energy only payments for electricity for each location, season period and load level (Electricity extended SAM) (millions €)
$\mathrm{E\_I\_ENERGY}_{y,i,l,dp,db}$	Institutions energy only payments for electricity for each location, season period and load level (Electricity extended SAM) (millions €)
$\mathrm{E\_EX\_ENERGY}_{y,l,dp,db}$	Exports energy only payments for electricity for each location, season period and load level (Electricity extended SAM) (millions €)
$\mathrm{E\_II\_QE\_TDeO}_{y,gne}$	Electricity TDeO intermediate input expenditure in non-electric goods (Electricity extended SAM) (millions €)
$\mathrm{E\_II\_EE\_TDeO}_{y,l,dp,db}$	Electricity TDeO intermediate input expenditure in a determined electricity load level and period (Electricity extended SAM) (millions €)
$\mathrm{E\_F\_E\_TDeO}_{y,pf}$	Electricity TDeO production factors expenditure (Electricity extended SAM) (millions €)
$\mathrm{E\_TAX\_E\_TDeO}_{y,tx}$	Electricity TDeO taxes expenditure (Electricity extended SAM) (millions €)
$\mathrm{E\_M\_E\_TDeO}_{y}$	Electricity TDeO imports expenditure (Electricity extended SAM) (millions €)
$\mathrm{E\_II\_EQ\_POWER}_{y,sne}$	Non electric sector network payments for electricity (Electricity extended SAM) (millions €)
$\mathrm{E\_I\_POWER}_{y,i}$	Institutions network payments for electricity (Electricity extended SAM) (millions €)
$\mathrm{E\_EX\_POWER}_{y}$	Exports network payments for electricity (Electricity extended SAM) (millions €)

Auxiliary SAM cell accounts variables by cost type (fixed and variable):

$\mathrm{FIX\_*}$	Fixed costs component for each of the above electricity extended cell accounts
$\mathrm{VAR\_*}$	Variable costs component for each of the above electricity extended cell accounts
$\mathrm{TOTAL\_SURPLUS}_{y,l,gp,gb}$	Total generation economic surplus by load block after excluded variable costs

Parameters:

Original SAM cells:

$\overline{e\_ii}_{y,gne}^{elet}$	Electricity intermediate input expenditure in non-electric goods (Original SAM value)
$\overline{e\_ii}_{y}^{elet,elet}$	Electricity intermediate input expenditure in electricity (Original SAM value)
$\overline{e\_pf}_{y,pf}^{elet}$	Electricity production factors expenditure (Original SAM value)
$\overline{e\_tax}_{y,tx}^{elet}$	Electricity taxes expenditure (Original SAM value)
$\overline{e\_m}_{y}^{elet}$	Electricity imports expenditure (Original SAM value)
$\overline{e\_ii}_{y,sne}^{elet}$	Non electric sector demand payments for electricity (Original SAM value)
$\overline{e\_inst}_{y}^{elet}$	Institutions demand payments for electricity (Original SAM value)
$\overline{e\_ex}_{y}^{elet}$	Exports demand payments for electricity (Original SAM value)

Initial values of technological parameters used in the calibration:

$\overline{\mathrm{oem\_vom}}_{y,t}$	operation and maintenance variable costs (€/MWh)
$\overline{\mathrm{oem\_fom}}_{y,l,t}^{labor}$	operation and maintenance labor fixed costs (€/KW)
$\overline{\mathrm{oem\_fom}}_{y,l,t}^{sc}$	operation and maintenance social contribution fixed costs fixed costs (€/KW)
$\overline{\mathrm{oem\_fom}}_{y,l,t}^{equip}$	operation and maintenance equipment fixed costs (€/KW)
$\bar{\eta}_{y,l,t}$	thermodynamic efficiency (MWh/kg)
$\overline{\mathrm{own\_cons}}$	initial own consumption of electricity by the generation activity (%)
$\overline{\mathrm{overn\_costs}}_{y,t}$	overnight new capacity investment costs (€/KW)
$\overline{\mathrm{loss}}_{y,l,p,b}$	transmission and distributions losses proportion
$\overline{\mathrm{co2}}_{t,f}^{fuel\_content}$	co2 emission potential by combustible (MMtCO2e/ MWh)

Auxiliary parameters:

$\overline{\mathrm{pgen}}_{y,t,f,l,gp,gb}$	Electricity power generation by each technology (MW)
$\overline{\mathrm{tcap}}_{y,l,t}$	Total installed capacity potency
$\overline{\mathrm{ppumped}}_{y,l,p,b}$	Pumping consumed electricity power (MW)

$\overline{\text{pins}}_{y',l,t}$	New installed capacity by year
$\overline{\text{p}}^{\text{energy only}}_{y,l.dp,db}$	Energy only electricity price by block
$\overline{\text{dist\_factor}}_{y,l,p,b}$	Factor responsible to distribute the fixed cost payments between the different load blocks and periods according their respective generation economic surplus
$\overline{\text{tx\_aliq}}_{tx}$	Electricity taxes aliquot
$\overline{\text{demand\_by\_agent}}_{y,SAM,l,dp,db}$	electricity demanded by agent described in the SAM (MWh)
$\overline{\text{dur}}_{l,p,b}$	load block duration (hours)
$\overline{\text{cap}}^{\text{to\_be\_amort}}_{y,l,t}$	power plant technology existent installed capacity not amortized (including exclusion of installed capacity previous liberalization, 1997, considered already paid as stranded costs) (MW)
$\overline{\text{p}}^{\text{fuel}}_{y,p,t,f}$	fuel price: enriched uranium (€/Kg), coal (€/t), gas natural (€/miles m3) and fuel-oil (€/t diesel)
$\overline{\text{pimp}}_{y,l,p,b}$	Generated potency imported (MWh)
$\overline{\text{idc}}_{t}$	accumulated interest during construction
$\overline{\text{crf}}_{t}$	Capital recovery factor, i.e., accumulated discount payments during amortization

Calibration Problem Equations:

Objective function: $\text{Min} \quad \sum_c \text{MAX\_PCTG\_DEV}_y^c$

Subject to:

First Group: Chebyshev deviation equations**:**

Variable O&M costs:

$$\text{OeM\_VOM}_{y,t} - \overline{\text{oem\_vom}}_{y,t} + \text{N\_DEV\_OeM\_VOM}_{y,t} - \text{P\_DEV\_OeM\_VOM}_{y,t} = 0$$

$$\frac{\text{N\_DEV\_OeM\_VOM}_{y,t} + \text{P\_DEV\_OeM\_VOM}_{y,t}}{\overline{\text{oem\_vom}}_{y,t}} \leq \text{MAX\_PCTG\_DEV}_y^{\text{OeM\_VOM}}$$

Fixed O&M labor:

$$\text{OeM\_FOM}^{\text{labor}}_{y,l,t} - \overline{\text{oem\_fom}}^{\text{labor}}_{y,l,t} + \text{N\_DEV\_OeM\_FOM}^{\text{labor}}_{y,l,t} - \text{P\_DEV\_OeM\_FOM}^{\text{labor}}_{y,l,t} = 0$$

$$\frac{\text{N\_DEV\_OeM\_FOM}^{\text{labor}}_{y,l,t} + \text{P\_DEV\_OeM\_FOM}^{\text{labor}}_{y,l,t}}{\overline{\text{oem\_fom}}^{\text{labor}}_{y,l,t}} \leq \text{MAX\_PCTG\_DEV}_y^{\text{OeM\_FOM}^{labor}}$$

Fixed O&M taxes costs:

$$\mathrm{OeM\_FOM}_{y,l,t}^{sc} - \overline{\mathrm{oem\_fom}}_{y,l,t}^{sc} + \mathrm{N\_DEV\_OeM\_FOM}_{y,l,t}^{sc} - \mathrm{P\_DEV\_OeM\_FOM}_{y,l,t}^{sc} = 0$$

$$\frac{\mathrm{N\_DEV\_OeM\_FOM}_{y,l,t}^{sc} + \mathrm{P\_DEV\_OeM\_FOM}_{y,l,t}^{sc}}{\overline{\mathrm{oem\_fom}}_{y,l,t}^{sc}} \leq \mathrm{MAX\_PCTG\_DEV}_{y}^{\mathrm{OeM\_FOM}^{sc}}$$

Fixed O&M equipment costs:

$$\mathrm{OeM\_FOM}_{y,l,t}^{equip} - \overline{\mathrm{oem\_fom}}_{y,l,t}^{equip} + \mathrm{N\_DEV\_OeM\_FOM}_{y,l,t}^{equip} - \mathrm{P\_DEV\_OeM\_FOM}_{y,l,t}^{equip} = 0$$

$$\frac{\mathrm{N\_DEV\_OeM\_FOM}_{y,l,t}^{equip} + \mathrm{P\_DEV\_OeM\_FOM}_{y,l,t}^{equip}}{\overline{\mathrm{oem\_fom}}_{y,l,t}^{equip}} \leq \mathrm{MAX\_PCTG\_DEV}_{y}^{\mathrm{OeM\_FOM}^{equip}}$$

Thermodynamic efficiency:

$$\eta_{y,t,f} - \bar{\eta}_{y,t,f} + \mathrm{N\_DEV\_}\eta_{y,t,f} - \mathrm{P\_DEV\_}\eta_{y,t,f} = 0$$

$$\frac{\mathrm{N\_DEV\_}\eta_{y,t,f} + \mathrm{P\_DEV\_}\eta_{y,t,f}}{\bar{\eta}_{y,t,f}} \leq \mathrm{MAX\_PCTG\_DEV}_{y}^{\eta}$$

Generation technologies own electricity consumption:

$$\mathrm{OWN\_CONS} - \overline{\mathrm{own\_cons}} + \mathrm{N\_DEV\_OWN\_CONS} - \mathrm{P\_DEV\_OWN\_CONS} = 0$$

$$\frac{\mathrm{N\_DEV\_OWN\_CONS} + \mathrm{P\_DEV\_OWN\_CONS}}{\overline{\mathrm{own\_cons}}} \leq \mathrm{MAX\_PCTG\_DEV}_{y}^{\mathrm{OWN\_CONS}}$$

New capacity overnight investment costs:

$$\mathrm{OVERN\_COSTS}_{y,t} - \overline{\mathrm{overn\_costs}}_{y,t} + \mathrm{N\_DEV\_OVERN\_COSTS}_{y,t} - \mathrm{P\_DEV\_OVERN\_COSTS}_{y,t} = 0$$

$$\frac{\mathrm{N\_DEV\_OVERN\_COSTS}_{y,t} + \mathrm{P\_DEV\_OVERN\_COSTS}_{y,t}}{\overline{\mathrm{overn\_costs}}_{y,t}} \leq \mathrm{MAX\_PCTG\_DEV}_{y}^{\mathrm{OVERN\_COSTS}}$$

TD&O losses proportion:

$$\mathrm{LOSS}_{y,l,p,b} - \overline{\mathrm{loss}}_{y,l,p,b} + \mathrm{N\_DEV\_LOSS}_{y,l,p,b} - \mathrm{P\_DEV\_LOSS}_{y,l,p,b} = 0$$

$$\frac{\mathrm{N\_DEV\_LOSS}_{y,l,p,b} + \mathrm{P\_DEV\_LOSS}_{y,l,p,b}}{\overline{\mathrm{loss}}_{y,l,p,b}} \leq \mathrm{MAX\_PCTG\_DEV}_{y}^{\mathrm{LOSS}}$$

CO2e content by generation technology and fuel type used:

$$\mathrm{CO2e\_CONTENT_{y,t,f}} - \overline{\mathrm{co2}}_{\mathrm{t,f}}^{\mathrm{fuel\_content}} + \mathrm{N\_DEV\_CO2e\_CONTENTS_{y,t,f}} - \mathrm{P\_DEV\_CO2e\_CONTENTS_{y,t,f}} = 0$$

$$\frac{\mathrm{N\_DEV\_CO2e\_CONTENTS_{y,t,f}} + \mathrm{P\_DEV\_CO2e\_CONTENTS_{y,t,f}}}{\overline{\mathrm{co2}}_{\mathrm{t,f}}^{\mathrm{fuel\_content}}} \leq \mathrm{MAX\_PCTG\_DEV}_y^{\mathrm{CO2e\_CONTENT}}$$

<u>Export Price adjust (difference between internal market prices and export prices):</u>

$$P\_EXP\_ADJ_{\mathrm{y,l.dp,db}} - 1 + \mathrm{N\_DEV\_}P\_EXP\_ADJ_{\mathrm{y,l.dp,db}} - \mathrm{P\_DEV\_}P\_EXP\_ADJ_{\mathrm{y,l.dp,db}} = 0$$

$$\mathrm{N\_DEV\_}P\_EXP\_ADJ_{\mathrm{y,l.dp,db}} + \mathrm{P\_DEV\_}P\_EXP\_ADJ_{\mathrm{y,l.dp,db}} \leq \mathrm{MAX\_PCTG\_DEV}_y^{P\_EXP\_ADJ}$$

<u>Import Price adjust (difference between internal market prices and export prices):</u>

$$P\_IMP\_ADJ_{\mathrm{y,l.dp,db}} - 1 + \mathrm{N\_DEV\_}P\_IMP\_ADJ_{\mathrm{y,l.dp,db}} - \mathrm{P\_DEV\_}P\_IMP\_ADJ_{\mathrm{y,l.dp,db}} = 0$$

$$\mathrm{N\_DEV\_}P\_IMP\_ADJ_{\mathrm{y,l.dp,db}} + \mathrm{P\_DEV\_}P\_IMP\_ADJ_{\mathrm{y,l.dp,db}} \leq \mathrm{MAX\_PCTG\_DEV}_y^{P\_IMP\_ADJ}$$

<u>Second Group: SAM 'Must follow' accountability constraints</u>**:**

$$\overline{e\_ii}_{y,gne}^{elet} = \mathrm{E\_II\_QE\_TDeO_{y,gne}} + \sum_{\mathrm{l,gp,gb,t}} \mathrm{E\_II\_QE\_GEN_{y,gne,l,gp,gb,t}}$$

$$\overline{e\_pf}_{y,pf}^{elet} = \mathrm{E\_F\_E\_TDeO_{y,pf}} + \sum_{\mathrm{l,gp,gb,t}} \mathrm{E\_F\_E\_GEN_{y,pf,l,gp,gb,t}}$$

$$\overline{e\_tax}_{y,tx}^{elet} = \mathrm{E\_TAX\_E\_TDeO_{y,tx}} + \sum_{\mathrm{l,gp,gb,t}} \mathrm{E\_TAX\_E\_GEN_{y,tx,l,gp,gb,t}}$$

$$\overline{e\_m}_{y}^{elet} = \mathrm{E\_M\_E\_TDeO_{y}} + \sum_{\mathrm{l,gp,gb}} \mathrm{E\_M\_E\_GEN_{y,l,gp,gb}}$$

$$\overline{e\_ii}_{y,sne}^{elet} = \mathrm{E\_II\_EQ\_POWER_{y,sne}} + \sum_{\mathrm{l,dp,db}} \mathrm{E\_II\_EQ\_ENERGY_{y,sne,l,dp,db}}$$

$$\overline{e\_inst}_{y}^{elet} = \mathrm{E\_I\_POWER_{y,i}} + \sum_{\mathrm{l,dp,db}} \mathrm{E\_I\_ENERGY_{y,i,l,dp,db}}$$

$$\overline{e\_ex}_{y}^{elet} = \mathrm{E\_EX\_POWER_{y}} + \sum_{\mathrm{l,dp,db}} \mathrm{E\_EX\_ENERGY_{y,l,dp,db}}$$

Third Group: Micro-founded macroeconomic aggregates:

Electricity generation sector fuel and equipment intermediate inputs demand:

$$\mathrm{E\_II\_QE\_GEN}_{y,gne,l,gp,gb,t} = \mathrm{VAR\_E\_II\_QE\_GEN}_{y,gne,l,gp,gb,t} + \overline{\mathrm{dist\_factor}}_{y,l,p,b}\mathrm{FIX\_E\_II\_QE\_GEN}_{y,gne,l,t}$$

$$\mathrm{VAR\_E\_II\_QE\_GEN}_{y,gne,l,gp,gb,t} = \frac{\eta_{y,l,t}\ \bar{p}^{fuel}_{y,p,t,f}\left(\sum_f \overline{\mathrm{pgen}}_{y,t,f,l,gp,gb}\right)\overline{\mathrm{dur}}_{l,gp,gb}}{10^6}$$

$$\mathrm{gne} = \mathrm{coal, oil - nuclear\ and\ gas\ sectors}$$

$$\mathrm{VAR\_E\_II\_QE\_GEN}_{y,gne,l,gp,gb,t} = \frac{\mathrm{OeM\_VOM}_{y,t}\left(\sum_f \overline{\mathrm{pgen}}_{y,t,f,l,gp,gb}\right)\overline{\mathrm{dur}}_{l,gp,gb}}{10^6} \quad \mathrm{gne} = \mathrm{manufactures\ sector}$$

$$\mathrm{FIX\_E\_II\_QE\_GEN}_{y,gne,l,t} = \frac{\left(\mathrm{OeM\_FOM}^{equip}_{y,l,t}\right)\overline{\mathrm{tcap}}_{y,l,t}}{10^3} \qquad \mathrm{gne} = \mathrm{manufactures\ sector}$$

Electricity generation sector demand for electricity:

$$\mathrm{E\_II\_EE\_GEN}_{y,l,dp,dbgp,gb,t} = \mathrm{VAR\_E\_II\_EE\_GEN}_{y,l,dp,dbgp,,gb,t}$$

$$\mathrm{VAR\_E\_II\_EE\_GEN}_{y,l,dp,db,gp,gb,t} = \frac{\mathrm{OWN\_CONS}\left(\sum_f \overline{\mathrm{pgen}}_{y,t,f,l,gp,gb}\right)\overline{\mathrm{dur}}_{l,gp,gb}\bar{p}^{energy\ only}_{y,l.dp,db}}{10^6} + \frac{\overline{\mathrm{ppumped}}_{y,l,p,b}\overline{\mathrm{dur}}_{l,gp,gb}\bar{p}^{energy\ only}_{y,l.dp,db}}{10^6}$$

Electricity generation sector demand for production factors:

$$\mathrm{E\_F\_E\_GEN}_{y,pf,l,gp,gb,t} = \overline{\mathrm{dist\_factor}}_{y,l,gp,gb}\overline{\mathrm{dur}}_{l,gp,gb}\mathrm{FIX\_E\_F\_E\_GEN}_{y,pf,l,t}$$

$$\mathrm{FIX\_E\_F\_E\_GEN}_{y,pf,l,t} = \frac{\left(\mathrm{OeM\_FOM}^{labor}_{y,l,t}\right)\overline{\mathrm{tcap}}_{y,l,t}}{10^3} \qquad \mathrm{pf} = \mathrm{Labor}$$

$$\mathrm{FIX\_E\_F\_E\_GEN}_{y,pf,l,t} = \frac{\mathrm{OVERN\_COSTS}_{y,t}\overline{\mathrm{idc}}_t\overline{\mathrm{crf}}_t\left(\overline{\mathrm{cap}}^{to\_be\_amort}_{y,l,t} + \sum_{\substack{y'\leq y \\ y'\geq y-l\_t}} \overline{\mathrm{pins}}_{y',l,t}\right)}{10^3} \qquad \mathrm{pf} = \mathrm{Capital}$$

Electricity generation sector taxes:

$$\mathrm{E\_TAX\_E\_GEN}_{y,tx,l,gp,gb,t} = \mathrm{VAR\_E\_TAX\_E\_GEN}_{y,tx,l,gp,gb,t} + \overline{\mathrm{dist\_factor}}_{y,l,p,b}\mathrm{FIX\_E\_TAX\_E\_GEN}_{y,tx,l,t}$$

$$\mathrm{VAR\_E\_TAX\_E\_GEN}_{\mathrm{y,tx,l,gp,gb,t}} = \frac{\overline{\mathrm{tx\_al\imath q}}_{\mathrm{tx}}\left(\sum_{gne}\mathrm{E\_II\_QE\_GEN}_{\mathrm{y,gne,l,gp,gb,t}} + \sum_{dp,db}\mathrm{E\_II\_EE\_GEN}_{\mathrm{y,l,dp,db,gp,gb,t}}\right)}{10^6}$$

$$\mathrm{tx} = \mathrm{Product\ tax}$$

$$\begin{aligned}\mathrm{VAR\_E\_TAX\_E\_GEN}_{\mathrm{y,tx,l,gp,gb,t}} &= \frac{\overline{\mathrm{tx\_al\imath q}}_{\mathrm{tx}}}{10^6}\Bigg(\sum_{gne}\mathrm{E\_II\_QE\_GEN}_{\mathrm{y,gne,l,gp,gb,t}} + \sum_{dp,db}\mathrm{E\_II\_EE\_GEN}_{\mathrm{y,l,dp,db,gp,gb,t}} \\ &+ \sum_{pf}\mathrm{E\_F\_E\_GEN}_{\mathrm{y,pf,l,gp,gb,t}} \\ &+ \overline{\mathrm{d\imath st\_factor}}_{\mathrm{y,l,p,b}}\overline{\mathrm{dur}}_{\mathrm{l,gp,gb}}\mathrm{FIX\_E\_TAX\_E\_GEN}_{\mathrm{y,Social\ contributions,l,t}} \\ &+ \mathrm{VAR\_E\_TAX\_E\_GEN}_{\mathrm{y,Product\ tax,l,gp,gb,t}}\Bigg) \qquad \mathrm{tx} = \mathrm{Production\ tax}\end{aligned}$$

$$\mathrm{VAR\_E\_TAX\_E\_GEN}_{\mathrm{y,tx,l,gp,gb,t}} = \sum_{f}\mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}}\ \overline{\mathrm{co2}}_{\mathrm{t,f}}^{\mathrm{fuel\_content}}\ \overline{\mathrm{p}}_{\mathrm{y}}^{\mathrm{CO2}}\overline{\mathrm{dur}}_{\mathrm{l,p,b}} \qquad \mathrm{tx} = \mathrm{CO2\ payments}$$

$$\mathrm{FIX\_E\_TAX\_E\_GEN}_{\mathrm{y,tx,l,t}} = \frac{\left(\mathrm{OeM\_FOM}_{\mathrm{y,l,t}}^{\mathrm{sc}}\right)\overline{\mathrm{tcap}}_{\mathrm{y,l,t}}}{10^3} \qquad \mathrm{tx} = \mathrm{Social\ contributions}$$

<u>Electricity generation sector electricity imports payments:</u>

$$\mathrm{E\_M\_E\_GEN}_{\mathrm{y,l,gp,gb}} = \mathrm{VAR\_E\_M\_E\_GEN}_{\mathrm{y,l,gp,gb}}$$

$$\mathrm{VAR\_E\_M\_E\_GEN}_{\mathrm{y,l,gp,gb}} = \frac{\overline{\mathrm{p\imath mp}}_{\mathrm{y,l,p,b}}\ \overline{\mathrm{dur}}_{\mathrm{l,gp,gb}}\overline{\mathrm{p}}_{\mathrm{y,l.dp,db}}^{\mathrm{energy\ only}}\,P\_IMP\_ADJ_{\mathrm{y,l.dp,db}}}{10^6}$$

<u>Electricity generation receipts from other productive sectors, institutions and exports:</u>

$$\mathrm{E\_II\_EQ\_ENERGY}_{\mathrm{y,sne,l,dp,db}} = \frac{\overline{\mathrm{demand\_by\_agent}}_{\mathrm{y,sne,l,dp,db}}\overline{\mathrm{dur}}_{\mathrm{l,gp,gb}}\overline{\mathrm{p}}_{\mathrm{y,l.dp,db}}^{\mathrm{energy\ only}}}{10^6}$$

$$\mathrm{E\_I\_ENERGY}_{\mathrm{y,i,l,dp,db}} = \frac{\overline{\mathrm{demand\_by\_agent}}_{\mathrm{y,i,l,dp,db}}\overline{\mathrm{dur}}_{\mathrm{l,gp,gb}}\overline{\mathrm{p}}_{\mathrm{y,l.dp,db}}^{\mathrm{energy\ only}}}{10^6}$$

$$\mathrm{E\_EX\_ENERGY}_{\mathrm{y,l,dp,db}} = \frac{\overline{\mathrm{demand\_by\_agent}}_{\mathrm{y,ex,l,dp,db}}\overline{\mathrm{dur}}_{\mathrm{l,gp,gb}}\bar{\mathrm{p}}^{\mathrm{energy\ only}}_{\mathrm{y,l.dp,db}}\,P\_EXP\_ADJ_{\mathrm{y,l.dp,db}}}{10^6}$$

TD&O electricity demand:

$$\begin{aligned}\mathrm{E\_II\_EE\_TDeO}_{\mathrm{y,l,dp,db}} &= \mathrm{LOSS}_{\mathrm{y,l,p,b}}\left(\sum_{\mathrm{t,f}}\overline{\mathrm{pgen}}_{\mathrm{y,t,f,l,p,b}} + \overline{\mathrm{pimp}}_{\mathrm{y,l,p,b}} + \overline{\mathrm{pexp}}_{\mathrm{y,l,p,b}}\right.\\ &\left. - \overline{\mathrm{ppumped}}_{\mathrm{y,l,p,b}}\right)\overline{\mathrm{dur}}_{\mathrm{l,dp,db}}\frac{\bar{\mathrm{p}}^{\mathrm{energy\ only}}_{\mathrm{y,l.dp,db}}}{10^6}\end{aligned}$$

Generation equilibrium between receipts and expenditures:

$$\begin{aligned}&\sum_{\mathrm{sne}}\mathrm{E\_II\_EQ\_ENERGY}_{\mathrm{y,sne,l,p,b}} + \mathrm{E\_II\_EE\_TDeO}_{\mathrm{y,l,p,b}} + \sum_{\mathrm{gp,gb,t}}\mathrm{E\_II\_EE\_GEN}_{\mathrm{y,l,p,b,gp,gb,t}}\\ &+ \sum_{\mathrm{i}}\mathrm{E\_I\_ENERGY}_{\mathrm{y,i,l,p,b}} + \mathrm{E\_EX\_ENERGY}_{\mathrm{y,l,p,b}}\\ &= \sum_{\mathrm{gne,t}}\mathrm{E\_II\_QE\_GEN}_{\mathrm{y,gne,l,p,b,t}} + \sum_{\mathrm{dp,db,t}}\mathrm{E\_II\_EE\_GEN}_{\mathrm{y,l,dp,db,p,b,t}}\\ &+ \sum_{\mathrm{pf,t}}\mathrm{E\_F\_E\_GEN}_{\mathrm{y,pf,l,p,b,t}} + \sum_{\mathrm{tx,t}}\mathrm{E\_TAX\_E\_GEN}_{\mathrm{y,tx,l,p,b,t}} + \mathrm{E\_M\_E\_GEN}_{\mathrm{y,l,p,b}}\\ &+ MKT\_FAILURES\_AND\_NON\_ACCOUNTED\_COSTS_{\mathrm{y,l,p,b}}\\ &+ \overline{\mathrm{rights}}^{\mathrm{CO2}}_{\mathrm{y,l,t}}\bar{\mathrm{p}}^{\mathrm{CO2}}_{\mathrm{y}}\left(\frac{\overline{\mathrm{pgen}}_{\mathrm{y,t,f,l,p,b}}\,\overline{\mathrm{co2}}^{\mathrm{fuel\_content}}_{\mathrm{t,f}}\,\overline{\mathrm{dur}}_{\mathrm{l,p,b}}}{\sum_{t`,f`,l`,p`,b`}\left(\overline{\mathrm{pgen}}_{\mathrm{y,t`,f`,l`,p`,b`}}\,\overline{\mathrm{co2}}^{\mathrm{fuel\_content}}_{\mathrm{t`,f`}}\,\overline{\mathrm{dur}}_{\mathrm{l`,p`,b`}}\right)}\right)\end{aligned}$$

TD&O equilibrium between receipts and expenditures:

$$\begin{aligned}&\sum_{gne}\mathrm{E\_II\_QE\_TDeO}_{\mathrm{y,gne}} + \sum_{l,dp,db}\mathrm{E\_II\_E\_TDeO}_{\mathrm{y,l,dp,db}} + \sum_{pf}\mathrm{E\_F\_E\_TDeO}_{\mathrm{y,pf}} + \sum_{tx}\mathrm{E\_TAX\_E\_TDeO}_{\mathrm{y,tx}}\\ &+ \mathrm{E\_M\_E\_TDeO}_{\mathrm{y}} = \sum_{sne}\mathrm{E\_II\_EQ\_POWER}_{\mathrm{y,sne}} + \sum_{i}\mathrm{E\_I\_POWER}_{\mathrm{y,i}} + \mathrm{E\_EX\_POWER}_{\mathrm{y}}\end{aligned}$$

Annex II – The Electricity Power Generation Operation and Expansion Planning Model

Variables:

$PGEN_{y,t,f,l,p,b}$	Electricity power generation by each technology (MW)
$PPUMPED_{y,l,p,b}$	Pumping consumed electricity power (MW)
$RES_{y,l,p}$	Hydro technology reservoir level (MW)
$TCAP_{y,l,t}$	Total installed capacity potency
$PINS_{y,l,t}$	New installed capacity by year

Parameters:

$\overline{oem\_vom}_{y,t}$	operation and maintenance variable costs (€/MWh)
$\overline{oem\_fom}_{y,l,t}^{labor}$	operation and maintenance labor fixed costs (€/KW)
$\overline{oem\_fom}_{y,l,t}^{sc}$	operation and maintenance social contribution fixed costs fixed costs (€/KW)
$\overline{oem\_fom}_{y,l,t}^{equip}$	operation and maintenance equipments fixed costs (€/KW)
$\bar{\eta}_{y,l,t}$	Thermodynamic efficiency (MWh/kg)
$\overline{own\_cons}$	Initial own consumption of electricity by the generation activity (%)
$\overline{overn\_costs}_{y,t}$	Overnight new capacity investment costs (€/KW)
$\overline{loss}_{y,l,p,b}$	Transmission and distributions losses proportion
$\overline{dur}_{l,p,b}$	load block duration (hours)
$\overline{cap}_{y,l,t}$	power plant technology existent installed capacity (MW)
$\overline{cap}_{y,l,t}^{to\_be\_amort}$	power plant technology existent installed capacity not amortized (including exclusion of installed capacity previous liberalization, 1997, considered already paid as stranded costs) (MW)
$\bar{p}_{y,p,t,f}^{fuel}$	fuel price: enriched uranium (€/Kg), coal (€/t), gas natural (€/miles m3) and fuel-oil (€/t diesel)
$\overline{demand}_{y,l,p,b}$	electricity power demanded (households, non-electricity sectors and exports) (MW)
$\overline{pctg}_{y,l}^{foil\_on\_fg}$	Percentage of fuel-oil combustible used on Fuel-Gas technology (%)
$\overline{pgen\_base\_year}_{l,p,b,t}$	Generated potency in the base year (MW)
$\overline{pimp}_{y,l,p,b}$	Generated potency imported (MW)
$\overline{pexp}_{y,l,p,b}$	Generated potency exported (MW)
$\overline{inflows}_{y,l,p}$	hydroelectric reservoir inflows (MW)
$\overline{ror\_inflows}_{y,l,p}$	hydroelectric run of river inflows (MW)
$\overline{eff}^{Pump}$	Pumping technologies efficiency (%)
$\overline{res\_max}_{y,l,t}$	maximum reservoir level (MWh)

$\overline{\text{availability}}_{y,l,t}$	mean availability of technology (%)
$\overline{\text{premium}}_{t,f}^{renew}$	technology renewable premium (€/MWh)
$\overline{\text{rights}}_{y,l,t}^{CO2}$	technology emission rights given by the government (MMtCO2e)
$\overline{\text{co2}}_{t,f}^{fuel\_content}$	co2 emission potential by combustible (MMtCO2e/ MWh)
$\bar{p}_{y}^{CO2}$	co2 price (€/tCO2)
$\overline{\text{non\_intt\_coverage}}$	Capacity reserve required in non-intermittent generation technologies for the higher demanding load block
$\overline{\text{idc}}_{t}$	accumulated interest during construction
$\overline{\text{crf}}_{t}$	Capital recovery factor, i.e., accumulated discount payments during amortization

Min:

$$\sum_{t,f,p,b} \overbrace{\frac{\text{PGEN}_{y,t,f,l,p,b}\ \bar{\eta}_{y,l,t}\ \bar{p}_{y,p,t,f}^{fuel}\ \overline{\text{dur}}_{l,p,b}}{10^6}}^{\text{Fuel cost}} + \sum_{t,f,p,b} \overbrace{\frac{\text{PGEN}_{y,t,f,l,p,b}\ \overline{\text{co2}}_{t,f}^{fuel\_content}\ \bar{p}_{y}^{CO2}\overline{\text{dur}}_{l,p,b}}{10^6}}^{\text{CO}_2\text{ emission costs}}$$

$$+ \sum_{t,f,p,b} \overbrace{\frac{\text{PGEN}_{y,t,f,l,p,b}\overline{\text{oem\_vom}}_{y,t}\overline{\text{dur}}_{l,p,b}}{10^6}}^{\text{Variable O\&M equipament costs}} - \sum_{t,f,p,b} \overbrace{\frac{\text{PGEN}_{y,t,f,l,p,b}\overline{\text{premium}}_{t,f}^{renew}\overline{\text{dur}}_{l,p,b}}{10^6}}^{\text{Renewable premiun income}}$$

$$+ \sum_{t} \overbrace{\frac{\left(\overline{\text{oem\_fom}}_{y,l,t}^{labor} + \overline{\text{oem\_fom}}_{y,l,t}^{sc} + \overline{\text{oem\_fom}}_{y,l,t}^{equip}\right)\text{TCAP}_{y,l,t}}{10^3}}^{\text{Fixed O\&}M\text{ costs}}$$

$$+ \sum_{t} \overbrace{\frac{\overline{\text{overn\_costs}}_{y,t}\overline{\text{idc}}_{t}\overline{\text{crf}}_{t}\left(\overline{\text{cap}}_{y,l,t}^{to\_be\_amort} + \sum_{\substack{y' \le y \\ y' \ge y-l\_t}} \text{PINS}_{y',l,t}\right)}{10^3}}^{\text{Installed capacity amortization costs paid in the year}}$$

$$- \sum_{t,f,p,b} \overbrace{\overline{\text{rights}}_{y,l,t}^{CO2}\bar{p}_{y}^{CO2}}^{\text{Emission rights}} \qquad \forall y, l$$

Subject to:

<u>Demand balance:</u>

$$\overline{\text{demand}}_{y,l,p,b} \le \sum_{t,f} \text{PGEN}_{y,t,f,l,p,b} + \overline{\text{pimp}}_{y,l,p,b} - \text{PPUMPED}_{y,l,p,b} - (\overline{\text{own\_cons}}) \sum_{t,f} \text{PGEN}_{y,t,f,l,p,b}$$
$$- \overline{\text{loss}}_{y,l,p,b}\left(\sum_{t,f} \text{PGEN}_{y,t,f,l,p,b} + \overline{\text{pimp}}_{y,l,p,b} + \overline{\text{pexp}}_{y,l,p,b} - \text{PPUMPED}_{y,l,p,b}\right)$$

<u>Hydro reservoir management level:</u>

$$\overline{\text{inflows}}_{y,l,p} \ge \sum_{b} \text{PGEN}_{y,Hyd\_Res,na,l,p,b}\overline{\text{dur}}_{l,p,b} - \text{RES}_{y,l,p} + \text{RES}_{y,l,p+1}$$

Hydro run of river production:

$$PGEN_{y,Hyd\_RoR,na,l,p,b}\overline{dur}_{l,p,b} \leq \overline{ror\_inflows}_{y,l,p}$$

Pumping efficiency:

$$PPUMPED_{y,l,p,b}\overline{eff}^{Pump} \geq \sum_{p,b} PGEN_{y,Pump,na,l,p,b}\overline{dur}_{l,p,b}$$

Maximum pumping capacity:

$$\sum_{p,b} PGEN_{y,Pump,na,l,p,b}\overline{dur}_{l,p,b} \leq \overline{res\_max}_{y,l,Pump}$$

Fixed use proportion of combustibles in Fuel-Gas power plants:

$$PGEN_{y,F-G,Fuel-oil,l,p,b} = \overline{pctg}_{y,l}^{foil\_on\_fg} \sum_{f} PGEN_{y,F-G,f,l,p,b}$$

Wind power production at each load block:

$$PGEN_{y,Wind,na,l,p,b} = \overline{pgen\_base\_year}_{l,p,b,Wind} \frac{TCAP_{y,l,Wind}}{\overline{cap}_{Base\ year,l,Wind}}$$

Other special regime renewable production at each load block:

$$PGEN_{y,ORSR,na,l,p,b} = \overline{pgen\_base\_year}_{l,p,b,ORSR} \frac{TCAP_{y,l,ORSR}}{\overline{cap}_{Base\ year,l,ORSR}}$$

Maximum production capacity:

$$PGEN_{y,t,f,l,p,b} \leq \overline{availability}_{y,l,t} TCAP_{y,l,t}$$

Maximum hydro reservoir capacity:

$$RES_{y,l,p} \leq \overline{res\_max}_{y,l,Hyd}$$

Total installed capacity:

$$TCAP_{y,l,t} = \overline{cap}_{y,l,t} + \sum_{\substack{y' \leq y \\ y' \geq y-life\_time}} PINS_{y',l,t}$$

Reserves (firm capacity reserves requirements in non-intermittent technologies):

$$\sum_{t\_non\_intt} TCAP_{y,l,t} \geq \overline{non\_intt\_coverage} \max_{p,b}\left(\overline{demand}_{y,l,p,b}\right)$$