

Introducing electricity load level detail into a CGE model – Part II – The GEMED model applied to a DR policy

Renato Rodrigues¹, Pedro Linares²

May 23, 2013

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 results of the case study clearly show the enhanced capability of this model for assessing complex policies with load shifting, demand profile changes and technology substitution. 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 II out of II and it focuses on an applied policy assessment using such model.

Keywords: Computable General Equilibrium (CGE), Electricity Demand Response.

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

¹ Corresponding author, email: renato.rodrigues@iit.upcomillas.es, tel.: +34 91 542-2800 Ext. 2755, fax: +34 91 542-3176. Instituto de Investigación Tecnológica, Comillas P. University, C/ Santa Cruz de Marcenado 26, 28015, Madrid, Spain.

² Instituto de Investigación Tecnológica, Comillas P. University; Economics for Energy; and Harvard Kennedy School.

1 Introduction

...

2 CGE model

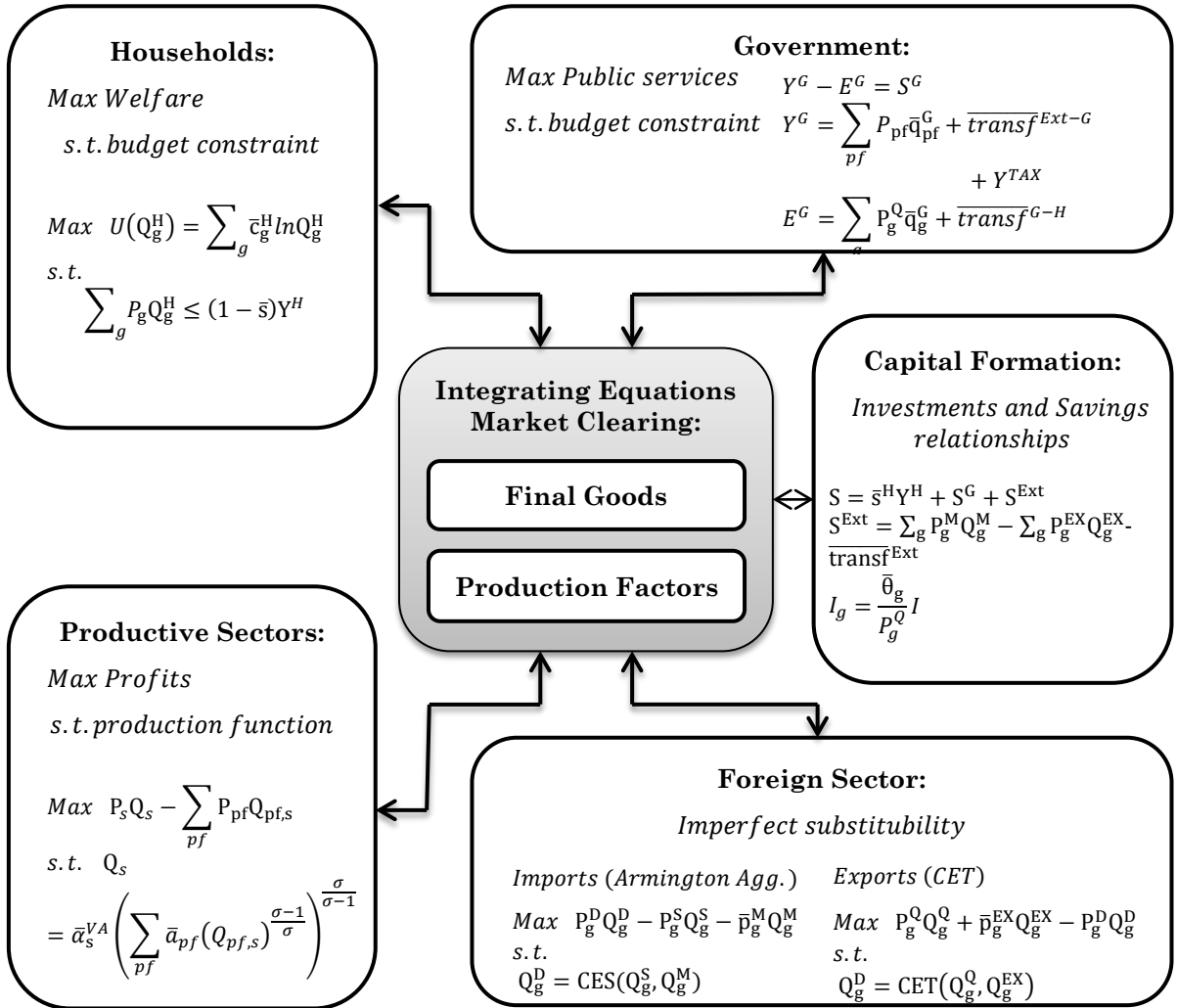
GEMED is a static, open economy, CGE model applied to a single country. The algebraic formulation follows a system of non-linear inequalities in the Arrow-Debreu general equilibrium framework. The model is implemented in GAMS and uses the PATH solver to obtain a local optimal equilibrium point.

The functional forms and data requirements necessary to define the model are described below. The description of the equations and an exhaustive explanation of the model can be found in Annex I.

2.1 General Structure

The model assumes two production factors, labor and capital, perfectly mobile across sectors and allocated according to a perfectly competitive factors' market. Figure 1 presents the general structure of the CGE model developed on this work.

Figure 1. Schematic CGE model structure and main equations.



Source: own elaboration. The complete model can be found at Annex I.

The production decision of each sector follows a profit maximization behavior and is represented by a series of nested production functions, except for the electricity sector case. The production factors are combined in a constant elasticity of substitution (CES) function. The resulting value-added composite is combined with the intermediate inputs through a Leontief assumption of fixed use proportion in order to define the final sector production.

The model comprises seven representative sectors according to their relationship with the electricity sector: the electricity sector itself, three fuel supplier sectors (Carbon, Oil/Nuclear and Gas), two typical electricity demanders besides

households (Food and Manufactures and Services)³ and one energy intensive sector (Transport).

Each productive sector supplies one commodity, except again for the electricity case. We assume that goods are differentiated according to their sources (domestic and foreign countries). Domestic goods are combined with imported goods to produce an equivalent composite good through an Armington aggregation, under a small country assumption. The total supplied composite good is confronted with the external and internal demand for goods. Primarily, the amount of goods aimed to exports and the amount heading for the domestic market are divided by the use of a constant elasticity of transformation function (CET). Finally, the remaining domestic goods supply faces the domestic agents' consumption decision represented by the demand of institutions (government and households), the sectors' intermediate input demand and the investment goods demand.

We assume an expenditure linear demand system for the utility maximization problem of the households. The production factors dotation and the economic transfers received from the government and from the exterior determine the household available income for consumption after excluding savings.

The public sector acts as an owner (of capital and foreign transfers) and as a redistributor of the resources acquired by different transfers and taxes (social contributions, value added taxes, indirect product and production taxes, renewable subsidies, and CO2 allowances distribution). We assume an endogenous public savings level and also that the government consumption is a fixed proportion of government expenditure. The provision of public services does not follow these restrictive assumptions. They are aggregated in the services sectors and are modeled assuming factors substitution and the use of intermediate inputs as described above for the productive sectors.

³ As we will see, this big aggregation level is enough to represent the importance of electricity time and location considerations on electricity policies, while keeping a manageable description of results in this paper. More policy oriented papers should consider a more exhaustive representation of production sectors according to the policy consequences to be evaluated.

All savings are assumed to be spent in investment goods at fixed investment shares for each sector. Due to the relative prices characteristic of the general equilibrium model, a consumer price index is adopted as the numeraire in the model.

2.2 The Electricity Sector Structure

The electricity sector definition requires a more extensive description. The electricity commodity is differentiated in two groups of electricity goods to represent the energy and capacity components of electricity.

The capacity component includes the Transmission, Distribution and Other activities in the sector (TD&O) and is represented by a unique aggregate electricity power product. For the sake of simplicity, and given the policy assessment requirements presented at this paper we chose to adopt a relatively simple network component (TD&O) description⁴. The TD&O activity follows a traditional Leontief aggregation structure for combining the production factors and different intermediate inputs into a single TD&O (see Figure 2a).

In turn, the energy component (GEN) is represents the electricity generation decisions and is disaggregated much further. The structure chosen aims to represent two important features of the electricity commodity: the product heterogeneity between load blocks (in time and location) and the commodity homogeneity within the same period.

The heterogeneity in location and time is a direct result of the use of different technologies, operation restrictions, import profiles, distribution of fixed costs payments and market imperfections rents between different load blocks. Meanwhile, the commodity homogeneity within each load block represents the fact that two electrons are indistinguishable between each other if they are transiting by the same network at the same time. This feature is represented in the model by the use of a perfect substitute good produced by different technology power plants whenever this production takes place in the same load block.

⁴ A deeper policy assessment could make use of the same framework defined at this paper and the part I of this work in order to add electricity heterogeneity in time and location to the network component of the sector, however this work opted to take out such complications aiming a more clear description.

Figure 2 summarizes the differences between a CGE model traditional production sector decision, an electricity technology disaggregated electricity sector representation and the proposed GEMED electricity generation productive structure.

Figure 2a. Productive sector structure in a traditional CGE model.

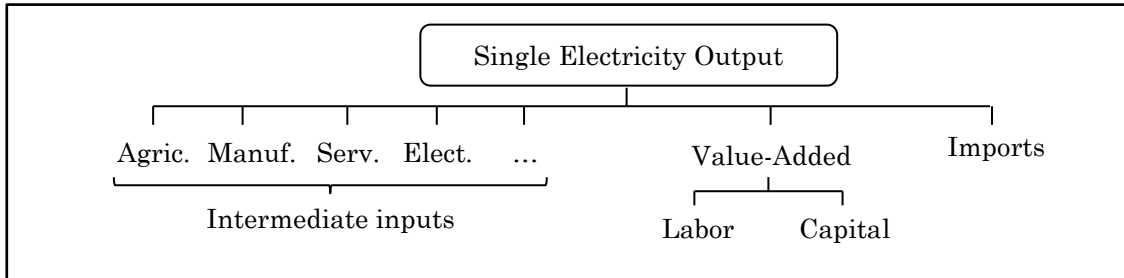


Figure 2b. Technology disaggregated electricity sector.

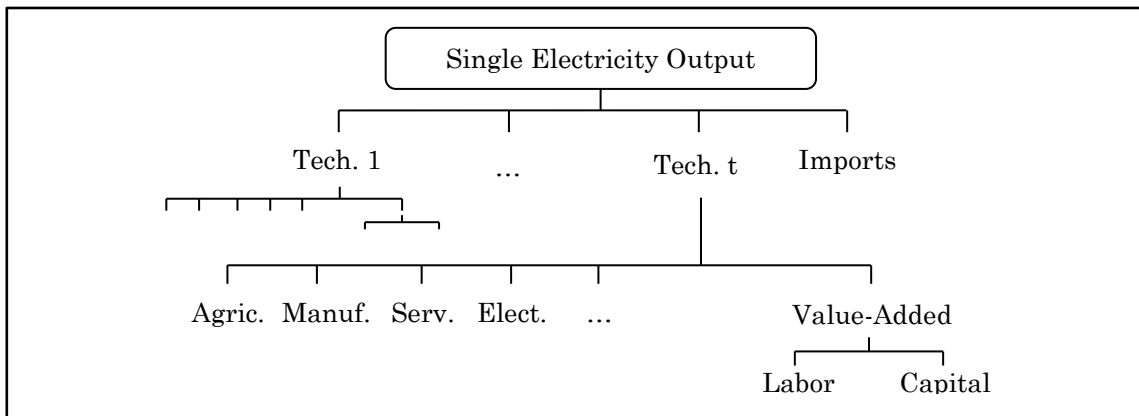
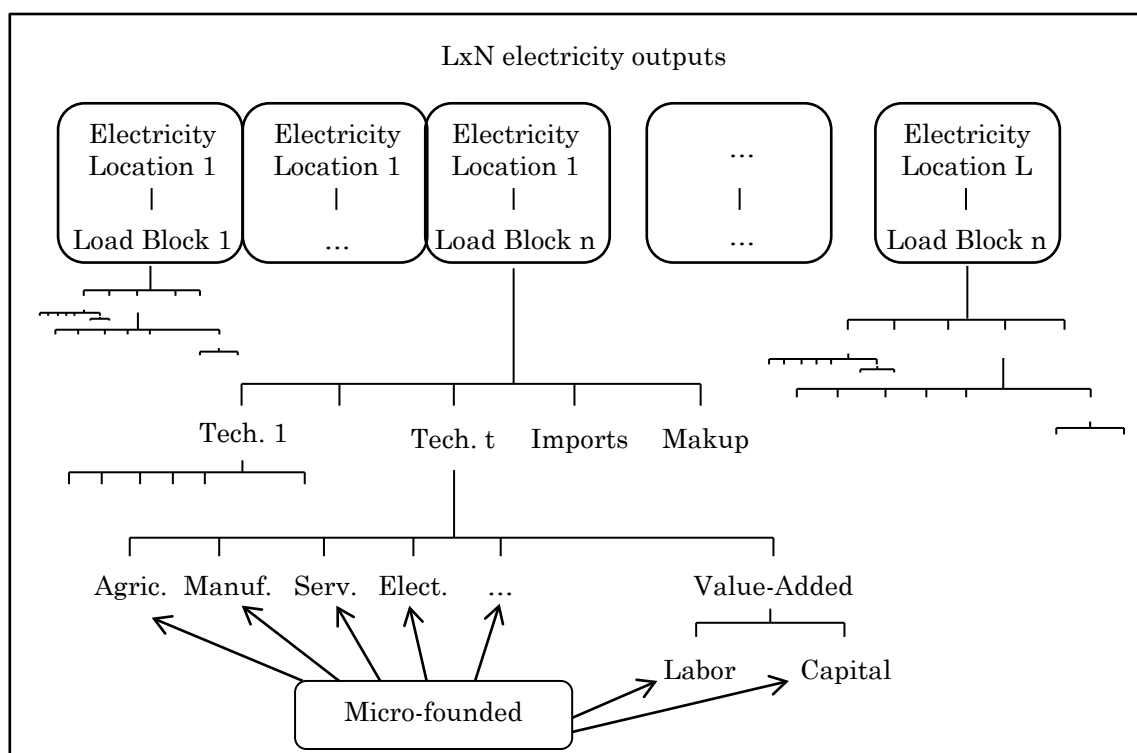


Figure 2c. GEMED electricity sector structure.



Source: own elaboration.

Besides the explicit representation of different electricity production technologies, the electricity detailed arrangement proposed by the GEMED model differentiates the energy component according to the network location (l locations)⁵ and, most particularly, by the time of consumption (n load blocks)⁶. The final GEN products are then represented by n times l dimensional vectors of prices and quantities, representing the different load blocks production (n) and demand decisions at different locations (l) (Figure 2c).

As a result the final CGE model is composed by $7+lxn$ goods and sectors: three for the fuel sectors, three for the typical electricity and energy demanders, one for the electricity TD&O and lxn for the electricity GEN products (one electricity energy product for each load block n at each location l assumed).

⁵ Two independent markets defined by their geographical characteristics are considered in the Spanish case study presented in this paper: the peninsular and the extra peninsular geographical regions.

⁶ The different levels of load aggregation used to illustrate the advantages of adopting the load level disaggregation for electricity policy evaluations are described in detail in section 3.

The advantages of the GEMED electricity detail become clearer when comparing the different structures presented in Figure 2. As can be seen, each electricity generation technology⁷ presents its own production function aggregation to combine production factors (labor and capital) and intermediate inputs. The biggest difference here when compared to a traditional CGE is that these technological parameters are defined to be equivalent to the variable and fixed costs of technical BU information (see part I of this paper, Rodrigues and Linares (2013)). As a result, the electricity generation technology costs in the CGE description are micro-founded by real world technological characteristics. This feature greatly increases the potential of the model for representing correctly technological evolution in time in the CGE assessment, as for example the inclusion of endogenous learning-by-doing processes in the policy evaluation.

Moving up in Figure 2c, all electricity production technologies produce a homogeneous electricity commodity within each load block. This commodity is then combined with imported electricity in order to provide the final electricity supplied for each load block. The limitations of existent network connections and historical electricity import profiles are used to exogenously determine the imported quantities at each load block.

Even so, the economic behavior of each load block is not yet completely described. As described in Rodrigues and Linares (2013), the presence of market imperfection rents, non-accounted costs and unevenly distributed fixed costs payments require accounting for an extra monetary component in each production period. The monetary flows obtained from the technologies' costs and import payments are therefore combined with a load block-dependable markup component in order to reflect the marginal price settlement in electricity markets and the presence of any market imperfection or non-accounted costs of the bottom-up data calibration process. This load block market surplus is estimated by the method described in Rodrigues and Linares (2013).

⁷ In this work we consider eleven different electricity production technologies: nuclear (Nuc), national coal (NCoal), imported coal (ICoal), combined cycle gas turbines (CCGT), fuel-oil and traditional gas turbines (F-G), hydropower with reservoir (Hyd_Res), hydropower run of river (Hyd_RoR), wind (Wind), other renewables (ORSR), cogeneration (NRSR) and pumping units (Pump).

Finally, any additional sources of transfers and costs (as in the case of indirect taxes for electricity and carbon emissions allowances) are added to the electricity sector behavior. The resulting structure is finally capable of representing the production technologies homogeneity within load blocks, at the same time addressing the time and location heterogeneity between different load blocks by the use of independent electricity products.

2.3 Data requirements

One could argue that data requirements for a model that deals with both bottom-up and top-down components simultaneously would be underwhelming and would also decrease its generality and replicability for other policy assessments. This subsection intends to advocate in the opposite direction basically by pointing out the data sources used in this work and underlining that they do not differ from the typical data available and widely used on bottom-up or top-down models.

Starting from the top-down perspective, the data requirements for the GEMED model are not larger than those found in any other CGE based policy assessment, such as the OECD-Green (Burniaux, Martin, Nicoletti, & Martins, 1992) or EPPA models (Paltsev, Reilly, & Jacoby, 2005). Most of the macroeconomic data necessary to define the model were acquired from the Spanish National Institute of Statistics (“Instituto Nacional de Estadística”, INE) and were consolidated into a SAM for the reference year (2005). Worldwide databases as the Global Trade Analysis Project (GTAP) (Hertel & Horridge, 1997) could be used with the same intent in order to reproduce this analysis for different countries. Substitution and transformation elasticities are taken from relevant literature and also global databases like GTAP.

The bottom-up data description requires a more extensive data set. Firstly, for the demand side, we need to define the electricity demand of each agent at each specific time. This work assumes different electricity consumption profiles for each different sector, institution and foreign agent in the economy. Exports and imports electricity demand profiles are estimated from benchmark year data (Spanish electricity system operator database, REE-ESIOS). The household demand profile is estimated from the data for low-voltage consumption (1.0 and 2.0 tariff and market components information provided by the Spanish regulator, CNE).

Fuel producers (Coal, Oil/Nuclear and Gas) and the manufacturing sector are assumed to be interruptible electricity demanders and as assumed by the “Atlas de la Demanda Eléctrica Española” (Indel, REE, 1997) have a linear, flatter, consumption profile. The small electricity demand at the benchmark year for the transport sector is assumed to follow the total system profile demand.

The electricity sector profile is determined by the electricity generation technologies consumption, the pumping units electricity demand and the network losses on the system. Finally, the services sector has its profile determined by the residual hourly system profile after excluding all the above agents of the system.

All above demand profile assumptions are not strong assumptions and are easily adaptable and reproducible suppositions for policy assessments in other regions and countries according to their specific electricity consumption.

Regarding the electricity supply side data, the database greatly increases with the modeler’s desire of adding more detail to the sector. Nevertheless, the data set used is very similar to well-developed bottom-up models such as MARKAL/TIMES (Fishbone and Abilock, 1981) or MESSAGE (Messner and Strubegger, 2001).

The bottom-up information used in this work to describe the electricity production technologies includes power plants construction time, life time, overnight costs, O&M costs, availability factors, thermodynamic efficiency, fuel prices, pollutant emissions, emissions allowances and currently installed capacity, among others. For the Spanish case, this data was directly obtained from the national electricity system operator database (REE-ESIOS), the European Union Joint Research Centre reports and the U.S. Energy Information Agency.

All remaining parameters necessary to define the GEMED are a direct result of the calibration process described on Rodrigues and Linares (2013).

3 Case study: An evaluation of a demand response program in Spain with the GEMED model

In order to illustrate the capabilities of the extensions introduced by the GEMED model when dealing with energy-economy-environment (E3) policy evaluations we assess the consequences of a Demand Response (DR) program for household

electricity consumers in Spain. This program consists in sending consumers price signals to make them shift or reduce their electricity consumption to better adjust to the system requirements. Basically, the program will result in shifting loads from peak periods, and reducing loads across the board. This may also have indirect effects on electricity prices, and therefore, on the electricity demand from other sectors.

The model assumes that households will shift their loads whenever they achieve a minimum savings requirement of 5% on their electricity bills. The equations that describe such policy assessment and a summary of the key demand response decision parameters used on this simulation are described in Annex II.

A pure bottom-up (BU) model would represent well the changes in the electricity sector, but would not be able to measure the changes in electricity demand induced in other sectors by the reduction of electricity prices, nor the effects in the economy of these changes. In turn, a traditional CGE model would lack the detail required to assess changes in the time of use of electricity. This is therefore a program for which a model such as GEMED is particularly well suited. To show this, we will present results for assessments carried out with the GEMED model and also with a pure BU model (the same one used to calibrate GEMED, described in Rodrigues and Linares (2013)) and a traditional CGE model, all of them using the same dataset⁸.

Additionally, we will also illustrate how the potential of the GEMED model to correctly describe the impacts increases when more load blocks for electricity demand are used. This will also serve as an exercise to confirm the model scalability and feasibility when applied to complex policy assessments. The following table (Table 1) describes the load block simulation scenarios simulated with this intent.

⁸ Even the GEMED model still presents some inherent formulation limitations. This is due the fact that the general equilibrium model continues to make use of econometric production functions to reflect the combinations of electricity generation technologies (nuclear, CCGT, Wind, etc.). This production structure, unlike the BU costs minimization problem, is unable to retire noncompetitive technologies even when the peak demand reduction is very high. The resulting policy scenario electricity price variations are underestimated by this reason. This paper conclusions section will point some future research topics capable of surpassing such limitations, as it is the case of hybrid CGE-BU models.

Table 1. Simulation scenarios.

Scenario name	Number of load blocks	Description
LB_1	1	Typical CGE model 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.

The results obtained by the policy assessment and the comparison between the BU, the traditional CGE and the GEMED models are described in the next section.

3.1 Results

The DR demand saving levels are estimated by comparing the BU electricity demand and price levels against a counterfactual simulation that allows additional displacement and conservation measures to be taken by the consumer under the presence of an increase in DR (see Annex II for the DR simulation detailed equations).

The DR program global effect in the economy corresponds to a demand shock, which contracts the economic activity by the corresponding electricity demand contraction level, and a total income retraction because of the electricity demand shifts from expensive hours to cheaper load blocks. DR program promotes savings from conservation and load shifts in the order of 2% of the electricity operation costs in the reference year⁹ (see Table 2).

⁹ The results presented in this section for the BU and the TD models aggregates the two different Spanish regions considered in the original model for the sake of simplicity and brevity of explanations.

Table 2. Demand response policy BU results for the base year.

	Benchmark	DR policy	Potential DR policy savings		
	Total cost	Total cost	Total savings	Conservation	Displacement
	(10 ⁶ €)	(10 ⁶ €) (%)	(10 ⁶ €) (%)	(10 ⁶ €) (%)	(10 ⁶ €) (%)
LB_1	10164	10035 -1.26%	128 1.26%	128 1.26%	0 0.00%
LB_6	10292	10104 -1.82%	186 1.81%	169 1.64%	17 0.16%
LB_20	10299	10107 -1.87%	206 2.00%	172 1.67%	34 0.33%
LB_45	10277	10087 -1.85%	207 2.01%	171 1.67%	35 0.34%
LB_90	10277	10071 -2.00%	224 2.18%	184 1.79%	39 0.38%
LB_180	10303	10075 -2.21%	243 2.36%	198 1.92%	45 0.43%

Source: own elaboration.

The more load blocks are considered in the model simulation, the closer to the real operation of the electricity sector is the simulation. The resulting higher price disparity representation provides more incentives to consumers conserve and displace the electricity demand. Consequently, the more load blocks considered, the larger are the demand shock of the DR policy, the income retraction resulting from this shock, and the power system direct cost benefits of the DR program.

It should be reminded here that our goal is not to provide an exhaustive assessment of the DR program (we do not consider for example the impact on network congestions or investments), but to show the advantages of using our GEMED model for this evaluation when confronted with the BU and the non-time disaggregated CGE alternatives. Therefore, we only summarize the main consequences of this policy and use the results to evaluate the different models addressed in this paper¹⁰.

A very important fact can be underlined from the Table 2 results to justify the use of load blocks disaggregation in a CGE evaluation of an electricity policy. Under a

¹⁰ The work of Rodrigues et al. (2011) describes in more detail the DR general equilibrium assessment under a simple CGE model without load block disaggregation. The same policy assessment exercise could be applied as a future work to a CGE model with load block disaggregation as the GEMED model. Moreover, the estimated savings level obtained from this work should be considered only as a lower bound approximation of the DR benefits estimation. The electricity technologies aggregation level used (ten different technologies) flattens the peak behavior, under valuating the benefits that could be achieved by an increase on electricity demand flexibility.

single load block assumption (LB_1 scenario) the policy evaluation behaves as it would be applied to the usual technology-only disaggregated CGE. Because of the single electricity commodity formulation, this form is incapable of evaluating endogenously the load shifts effects necessary for a correct evaluation of DR programs benefits (or similarly the introduction of electric cars, the consequences of smart metering or smart grid flexibility, etc). This fact is clear when we look at the lack of savings due to load shifts under the LB_1 scenario described in Table 2.

As mentioned before, the GEMED model is able to account for indirect effects not considered by BU models. Namely, the impact of lower electricity prices on the electricity demand of other sectors, which in turn results in a higher overall electricity demand. Similar effects could also happen in capital production factor prices (as electricity is a highly intensive demander of capital), and to a lower degree for labor prices. The agents are also susceptible to more effects due to the presence of an income effect, whenever the savings in electricity costs are translated to the electricity prices, and an endogenous reduction of the DR attractiveness, as the lower prices reduce the potential savings of adopting DR measures.

The effects described above act in the opposite direction of the reduction in the BU electricity demand promoted by DR program. The results of the program are therefore dampened in a general equilibrium context. A partial equilibrium model does not take into account such consequences, thus overestimating the consequences of the DR program.

As expected, the results of the general equilibrium model reflect exactly this behavior. The percentage of electricity demand reduction in the BU model is larger than in the GEMED model in any of the load block disaggregation assessed (see Table 3)¹¹.

¹¹ The absolute values of the TD GEMED and the BU models quantities and prices are not directly comparable because the models depart from different parameter values. The BU parameters are based in the original technological information, whereas the TD parameters are based on the calibrated parameters. By this token, from now on most of the results presented in the paper focus on analyzing percentage changes between the benchmark and case study results.

Table 3. Electricity generation sector results for the GEMED model and the Bottom-Up model demand response evaluations.

	Income		Price		Quantity		Emissions		Final consumer savings	
	BU	GE	BU	GE	BU	GE	BU	GE	BU	GE
	%	%	%	%	%	% % dif.	% CO2e % Acid e	% CO2e % Acid e	10 ⁶ €	10 ⁶ € % dif.
LB_1	-1.10%	-0.83%	0.00%	0.19%	-1.10%	-1.01% -8.2%	-1.11% -0.32%	-1.01% -1.01%	147.20	109.59
LB_6	-1.35%	-0.87%	-0.19%	0.20%	-1.16%	-1.07% -8.3%	-1.57% -0.55%	-0.98% -0.98%	215.26	138.07
LB_20	-1.80%	-0.87%	-0.64%	0.21%	-1.17%	-1.08% -8.2%	-1.59% -0.56%	-1.00% -1.00%	291.23	140.35
LB_45	-3.66%	-0.92%	-2.41%	0.22%	-1.28%	-1.13% -11.2%	-1.58% -0.53%	-0.81% -0.81%	578.16	144.41
LB_90	-3.64%	-1.02%	-2.29%	0.22%	-1.38%	-1.23% -10.7%	-1.71% -0.57%	-0.83% -0.83%	573.32	159.01
LB_180	-4.65%	-1.14%	-3.26%	0.20%	-1.44%	-1.35% -6.5%	-1.88% -0.65%	-1.29% -1.29%	756.17	184.92

Source: own elaboration. Percentage variations and consumer savings are accounted in relation to the benchmark values. BU = bottom-up electricity operation and planning model results; GE = GEMED results.

Around 0,9% of the decrease in electricity demand shown by the BU model (of the 1,10% original reduction promoted by the program) are taken away when the general equilibrium indirect effects are considered in the LB_1 scenario. This corresponds to an 8.2% rebound on quantities saved by the program when the indirect effects are taken into account. This rebound could be as higher as 11,2% and 10,7% when comparing the LB_45 and LB_90 scenario results.

In both models the DR potential for consumer savings increases as the number of load blocks evaluated increases. This is reasonable because the more load blocks represented, the better the representation of electricity operation under lower and upper bound demand, the better the evaluation of more extreme electricity price levels, and consequently, the higher the incentives to apply DR measures. Even after considering the approximated 10% quantity rebound, the difference between the models' total economic savings is largely explained by the observed difference in prices.

GEMED prices vary much less (0.19% to 0.22%) and in the opposite direction when compared to the partial equilibrium results (0.00% to -3.26%). The different

directions arise from the fact that the BU model is a cost minimization model meanwhile GEMED follows a fixed economy production function. Therefore a reduction in demand levels would mean a shift of the supply curve under the BU model, meanwhile the GEMED model would achieve a new equilibrium by moving along the production function curve.

The advantages of taken into account the load blocks disaggregation on the CGE modeling are much more clear if we compare the traditional CGE technological disaggregated results (the LB_1 scenario, Table 4), with the GEMED model results with even a small number of load blocks, as in the scenario LB_6 (see Table 5).

Table 4. Typical CGE (GEMED DR_LB_1 scenario) simulation results.

		Prices		Quantities		Emissions
		Benchm.	DR	Benchm.	DR	% CO2e % Acid e
		p.u.	p.u. %	p.u.	p.u. %	
Products	Electricity GEN	53.64	53,74 0.1885%	247	245 -1.0133%	-1.11% -0.32%
	Electricity TD&O	1.00	1,02 -0.0051%	14826	14825 -0.0019%	-
	Manufacturing	1.00	1,00 -0.0161%	778107	778089 -0.0022%	0.01% 0.01%
	Coal	1.00	1,00 -0.0018%	2413	2397 -0.6711%	-0.67% -0.67%
	Oil/Nuclear	1.00	1,00 -0.0169%	32156	32156 0.0001%	0.02% 0.02%
	Gas	1.00	1,00 -0.0207%	7641	7613 -0.3748%	-0.37% -0.37%
	Transport	1.00	1,00 -0.0209%	75496	75503 0.0090%	0.02% 0.02%
	Other Services	1.00	1,00 -0.0183%	842818	842817 -0.0002%	0.00% 0.00%
Prod. Factors	Labor	1.00	1,00 -0.0060%	334314	334314 0.0000%	-
	Capital	1.00	1,00 -0.0368%	376643	376642 -0.0002%	-

Source: own elaboration. p.u. = per unit.

Prices and quantities in the table do not necessarily reflect real world units because the CGE model is a relative price model by definition. Only the energy component of electricity prices and quantities were adjusted at the calibration stage to reflect the initial sector demand (10^3 GW) and prices (€/MWh) conditions.

Table 5. GEMED LB_6 scenario 2005 results.

			Prices		Quantities		Emissions	
			Benchm.	DR	Benchm.	DR	% CO2e % Acid e	
			p.u.	p.u. %	p.u.	p.u. %		
Products	Electricity Generation	Holiday	Off-peak	53.64	53.83 0.35%	11	11 -0.99%	-0.97% -0.97%
			Medium	53.64	53.86 0.40%	40	40 -1.21%	-1.19% -1.19%
			Peak	53.64	53.88 0.45%	17	16 -1.40%	-1.41% -1.41%
		Workday	Off-peak	53.64	53.47 -0.32%	27	27 0.88%	0.87% 0.87%
			Medium	53.64	53.81 0.32%	108	107 -1.02%	-1.01% -1.01%
			Peak	112.76	113.46 0.62%	44	43 -2.12%	-2.13% -2.13%
		Pondered Total	64.14	64.27 0.20%	247	244 -1.07%	-1.57% -0.55%	
		Electricity TD&O	1	1.02 0.0165%	12579	12578 -0.0088%	-	
		Manufacturing	1	1.00 -0.0233%	778107	778075 -0.0040%	0.01% 0.01%	
		Coal	1	1.00 -0.0002%	2413	2397 -0.6439%	-0.64% -0.64%	
	Oil/Nuclear	1	1.00 -0.0246%	32156	32154 -0.0048%	0.02% 0.02%		
	Gas	1	1.00 -0.0300%	7641	7606 -0.4555%	-0.45% -0.45%		
	Transport	1	1.00 -0.0309%	75496	75506 0.0121%	0.03% 0.03%		
	Other Services	1	1.00 -0.0273%	842818	842805 -0.0015%	0.00% 0.00%		
Prod. Factors	Labor	1	1.00 -0.0137%	334314	334314 0.0000%	-		
	Capital	1	1.00 -0.0538%	374270	374267 -0.0007%	-		

Source: own elaboration. p.u. = per unit.

As can be seen in Table 5, the introduction of time differentiation for the electricity commodity allows representing much more accurately the price differences between peak and off-peak periods. The prices of GEMED LB_6 scenario vary from 53.64 €/MWh to 112.76 €/MWh (compared to a single price of 53.64 €/MWh on the traditional CGE), which allows a much better representation in the model of the incentives for emission reductions or other sectors peak load reductions. The increased policy assessment consequences of improving the electricity load block

information can be verified by comparing the increased pondered prices (0.20% vs. 0.1885%) and quantities (-1.07% vs. -1.0133%) variations under the scenario LB_6.

This corroborates the fact that average prices, like the ones used in the traditional CGE modeling approach, are insufficient to represent correctly the behavior of time-differentiated marginal markets like those in the electricity sector. A multiple electricity commodity representation with load block disaggregation like the one included in the GEMED model is able to represent much more accurately the electricity market behavior even under a pure TD approach and with a small number of load blocks.

If we examine closer the policy final quantities variation we can identify much easier the advantages of having the electricity commodity time differentiation on the CGE model. The table below (Table 6) reproduces the policy quantities variation consequences of the previous tables, focusing on the differences between the load block disaggregated scenarios.

Table 6. Normalized quantity effects differences between the electricity technology-only disaggregated CGE (LB_1) and the GEMED model (LB_6).

		Quantities		Relative Difference ⁽¹⁾
		LB_1	LB_6	$(Q_{LB_6} - Q_{LB_1}) \frac{Electricity}{Economy}$
		% Q_{LB_1}	% Q_{LB_6}	%
Products	Electricity GEN	-1.0133%	-1.07%	<u>-8.21%</u>
	Electricity TD&O	-0.0019%	-0.0088%	-1.08%
	Manufacturing	-0.0022%	-0.0040%	-0.28%
	Coal	-0.6711%	-0.6439%	<u>4.23%</u>
	Oil/Nuclear	0.0001%	-0.0048%	-0.76%
	Gas	-0.3748%	-0.4555%	<u>-12.60%</u>
	Transport	0.0090%	0.0121%	0.49%
	Other Services	-0.0002%	-0.0015%	-0.21%
Prod. Factors	Labor	0.0000%	0.0000%	0,00%
	Capital	-0.0002%	-0.0007%	-0,07%

Source: own elaboration. (1) The difference column is normalized by the share of electricity expenditures in comparison to the total economy levels in order to present a similar order of magnitude that would be obtained from an electricity sector only Bottom-up policy evaluation.

We can clearly see in the difference column (the third column on Table 6) that some sectors present much stronger differences when comparing the results from the single (LB_1) and the six (LB_6) load blocks scenarios. The important fact to underline is the concentration of changes on the electricity and fuel sectors.

The cause for the first one (an 8.21% higher variation under the LB_6 scenario) were already underlined in the previously paragraphs. The presence of displacement effects (null under a traditional CGE) and the better representation of load block prices under the LB_6 scenario potentiate the DR policy consequences evaluated. However it is in the fuel sectors that the microeconomic advantages of including time differentiation in a CGE electricity policy assessment gets more evident.

As previously mentioned the increase in DR incentivizes the consumers to change their time of consumption from peak to medium and lower price blocks. The most expensive units under these peakier load blocks suffer a corresponding demand

drop while the marginal units of medium and lower peak hours have an increase on their production levels for supplying this extra displaced consumption.

A bottom-up model easily represents this behavior on a cost minimization paradigm; however, a CGE model based on a traditional single commodity economy production function would only be able to represent such consequences if the modeler exogenously changes the production function technical parameters.

As can be seen by the results presented in Table 6, the GEMED model is able to reproduce much more accurately the microeconomic production decision dynamics. The peak marginal units (CCGTs) suffer a drop in demand around 12% while the medium load level units (Coal) increase their demand in 4.23% relative to the traditional CGE formulation.

This result is of utmost importance for any environmental assessment because this can promote perverse results under an unfavorable electricity technologies portfolio, as the one present at the Spanish case. The greenhouse effect emissions are slight increased by the displacement from a more environmental efficient CCGT power plant to a Coal power plant production¹².

Even so, the global effect of the DR response policy studied in our case study is still very favorable in an environmental perspective due the higher magnitude of the conservation effect when compared to the indirect rebound and displacement effects identified in this paper.

The results presented in this section showed therefore that the introduction of load blocks in the CGE model improves substantially the representation of the electricity sector and the electricity fuel supplier behavior, even when compared with an already detailed electricity technology CGE model. As more load blocks are considered, more substantial are the gains of information conveyed by the model, and more substantial are the improvements of the GEMED time disaggregated model when compared with pure CGE or technology extended alternatives.

¹² This effect is highly dependable of the installed capacity structure of the country or region studied. Under more common electricity systems with pollutant power plants concentrated at the peak periods the displacement effects would actually act in the opposite direction of this paper case study helping to drop even more the emissions levels.

Nevertheless, there is a clear tradeoff created between the dimensions added by considering time differentiated electricity products and the computer requirements. This work intended also to soften this concern about the GEMED model scalability by presenting results for load block disaggregation levels of up to 200 different time differentiated products¹³.

4 Conclusions

This paper has presented for the first time a CGE model formulated with within year temporal disaggregation, location differentiation and technological detail in the electricity sector representation. In addition, we have shown the feasibility of applying our GEMED model to a real-world problem, the assessment of a Demand Response program in Spain.

The case study evaluated takes into account the actual Spanish electricity facilities and technology availability, the electricity sector operation and future investments decision, and the national accounting data of the Spanish economy. We have also included two distinct electricity markets with different conditions, the peninsular and the extra-peninsular one. The DR policy assessment was applied to different levels of load block disaggregation in order to show the advantages of such an extension in energy policy evaluations carried out with CGE models.

The addition of load block disaggregation allowed the CGE model to assess endogenously the effects of load shifts, impossible to represent under a single load block assumption. Moreover, the GEMED model presented clear advantages while compared to BU and pure CGE models.

The GEMED model is able to reproduce rebound effects, in the order of 6-10% on the case study presented, impossible to attain under a pure BU formulation. Moreover, the electricity production decision is much better represented than in a

¹³ Information about simulations carried out to prove the model scalability with until 540 differentiated electricity products and two different electricity markets can be requested to the authors. However, while the memory requirements for introducing too many load blocks greatly increases, the marginal benefits of introducing more load blocks tend to decrease after a certain load block number. For example, the majority of long-run BU evaluations consider less than twenty (20) representative load blocks to simulate the electricity sector behavior relatively accurately (an exception can be made for power plant unit commitment specific studies).

CGE model as can be verified by the displacement from peak units to lower demand producing power plants, before unattainable under a non BU paradigm, which reflected a drop of gas powered power plants use (CCGTs) and an increase on the coal demand that in our case study reflects perverse side effect of the policy demand displacement consequences.

Therefore, the resulting GEMED TD model mimics the rich description of the electricity sector production decisions present in the BU electricity models without overlooking the indirect effects and inter-sectorial and institutional consequences of the energy policies.

This improved representation of electricity prices enriches the evaluation of indirect and rebound effects by the CGE modeling approach. The direct consequence of such an extension is a better representation of the policy consequences on other sectors.

Nevertheless, the results obtained by this paper are still susceptible to improvements. The GEMED electricity sector production structure still uses the Leontief formulation, and hence includes some inherent limitations. A partial equilibrium model allows that marginal technologies may be retired if not competitive. However, the Leontief formulation assumes a fixed proportion of technologies for each load block, which limits the retirement of more expensive technologies. Similarly, the inclusion of backstop technologies, very relevant in long run policy assessments, is also limited under this production function structure. Therefore, a clear field of future research is the change of the production function formulation, which would require moving to a completely integrated mixed complementarity hard-link hybrid TD-BU model. Research is currently under way to determine calibration procedures, equation formulations and decomposition techniques for such a model, and in particular, to using it in a real-world setting.

This hybrid approach would also allow for a much more detailed representation of the BU model, in particular for the inclusion of start-up costs, intermittent sources, which are also becoming more and more relevant in electricity systems with the large-scale introduction of renewables.

Acknowledgements

This paper is based on research partly funded by the CENIT-GAD project. We also acknowledge partial support from the Spanish Ministry of Economy and Competitiveness (ECO2009-14586-C02-01). All views expressed here, as well as any errors, are the sole responsibility of the authors.

References

- Burniaux, J., Martin, J., Nicoletti, G., & Martins, J. (1992). GREEN a multi-sector, multi-region general equilibrium model for quantifying the costs of curbing CO2 emissions: a technical manual. *OECD Economics Department Working Papers*, (116). doi:10.1787/744101452772
- Fishbone, L. G., & Abilock, H. (1981). Markal, a linear-programming model for energy systems analysis: Technical description of the bnl version. *Int. J. Energy Res.*, 5: 353–375. doi: 10.1002/er.4440050406.
- Hertel, T., & Horridge, M. (1997). GTAP Book-Essential Programs. *Center for Global Trade Analysis, Purdue*.
- Messner, S., & Strubegger, M. (2001). MESSAGE IV model. *International Institute for Applied Systems Analysis, Laxenburg, Austria*.
- Paltsev, S., Reilly, J., & Jacoby, H. (2005). The MIT emissions prediction and policy analysis (EPPA) model: version 4. *MIT Joint Program on the Science and Policy of Global Change*, (Report no. 125). Retrieved from <http://dspace.mit.edu/handle/1721.1/29790>
- Rodrigues, R., Linares, P., & Gómez-Plana, A. G. (2011). A CGE assessment of the impacts on electricity production and CO2 emissions of a residential demand response program in Spain. *Estudios de Economía Aplicada*, 29(2), 665–(36 pages).
- Rodrigues, Rodrigues, & Linares, P. (2013). Introducing electricity load level detail into a CGE model – Part I – The calibration methodology. *Energy Economics (under revision)*.

Annex I – The GEMED Model

The GEMED model is formulated as a mixed complementary problem to solve simultaneously the Karush-Kuhn-Tucker conditions assuming an interior solution of the agents' individual maximization problems (households, productive sectors, government, investments and external relationships). The dimensions, variables and equations are presented below.

Sets:

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

Variables:

Household:

$Q_{ey, gne}^H$	Household domestic non electricity goods demand
$Q_{ey, l, p, b}^{H_GEN}$	Household domestic electricity goods demand at location l - season p and load block b
Q_{ey}^{TDeO}	Household domestic electricity goods demand of transmission distribution and other electricity services
$P_{ey, pf}$	Price of production factor pf
Y_{ey}^H	Total household income

Non electricity productive sectors:

$Q_{ey, pf, sne}^{pf_SNE}$	Quantity of production factor pf utilized in a specific sector sne
$Q_{ey, sne}^{VA}$	Quantity of value added composite good produced by sector sne
$P_{ey, sne}^{VA}$	Price of value added composite good of a specific sector sne

$Q_{ey,gne,sne}^{II}$	Quantity of intermediary input g utilized by a specific sector sne
$Q_{ey,l,dp,db,sne}^{II_GEN_SNE}$	Quantity of electricity good intermediary input at location l - season p and load block b utilized by a specific non electricity sector sne
$Q_{ey,sne}^{II_TDeO_SNE}$	Quantity of transmission, distribution and other electricity services intermediary input utilized by a specific non electricity sector sne
$Q_{ey,sne}^S$	Quantity of the commodity produced by a specific sector sne
$P_{ey,gne}^S$	Price of commodity produced by a specific sector sne (without foreign aggregations and production taxes)
	<u>Imports Armington Aggregation:</u>
$Q_{ey,gne}^M$	Quantity of good gne imported from the exterior
$Q_{ey,gne}^D$	Quantity of aggregated imported and domestic produced supply of good gne
$P_{ey,gne}^D$	Price of Armington aggregated price of the good gne
	<u>Exports CET disaggregation:</u>
$Q_{ey,gne}^{EX}$	Quantity of goods gne exported to the exterior
$Q_{ey,gne}^Q$	Quantity of final domestic market supply of good gne
$P_{ey,gne}^Q$	Price of final domestic good gne
	<u>Transmission, distribution and other electricity services:</u>
$Q_{ey,pf}^{pf_TDeO}$	Quantity of production factor pf used in the transmission, distribution and other electricity services
$Q_{ey}^{VA_TDeO}$	Quantity of value added composite good produced by the transmission, distribution and other electricity services
$P_{ey}^{VA_TDeO}$	Price of value added composite good of the transmission, distribution and other electricity services
$Q_{ey,gne}^{II_GNE_TDeO}$	Quantity of non-electricity intermediary input gne utilized by the transmission, distribution and other electricity services
$Q_{ey,l,dp,db}^{II_GEN_TDeO}$	Quantity of electricity good intermediary input at location l - season dp and load block db utilized by the transmission distribution and other electricity services
$Q_{ey}^{II_TDeO_TDeO}$	Quantity of transmission, distribution and other electricity services good intermediary input utilized by the electricity transmission, distribution and other electricity services
Q_{ey}^S	Quantity of the commodity produced by the transmission distribution and other electricity services
P_{ey}^S	Price of commodity produced by the transmission distribution and other electricity services (without foreign aggregations and production taxes)
Q_{ey}^D	Quantity of aggregated imported and domestic produced supply of transmission distribution and other electricity services
P_{ey}^D	Price of aggregated transmission distribution and other electricity services
Q_{ey}^Q	Quantity of final domestic market supply of transmission distribution and other electricity services
P_{ey}^Q	Price of final domestic transmission distribution and other electricity services
	<u>Electricity generation productive sector:</u>
$Q_{ey,pf,l,p,b,t}^{pf_GEN_tech}$	Quantity of production factor pf used in the electricity sector at location l - season p and load block b by the production technology t

$Q_{ey,l,p,b,t}^{VA_GEN_tech}$	Quantity of value added composite good produced by the electricity sector at location l - season p and load block b by the production technology t
$P_{ey,l,p,b,t}^{VA_GEN_tech}$	Price of value added composite good of the electricity sector at location l - season p and load block b by the production technology t
$Q_{ey,gne,l,p,b,t}^{II_GNE_GEN_tech}$	Quantity of non-electricity intermediary input gne utilized by the electricity sector at location l - season p and load block b by the production technology t
$Q_{ey,l,dp,db,gp,gb,t}^{II_GEN_GEN_tech}$	Quantity of electricity good intermediary input at location l - season dp and load block db utilized by the electricity sector at season gp and load block gb by the production technology t
$Q_{ey,l,p,b,t}^{II_TDeO_GEN_tech}$	Quantity of electricity transmission, distribution and other electricity services good intermediary input utilized by the electricity sector at season p and load block b by the production technology t
$Q_{ey,l,p,b,t}^{S_GEN_tech}$	Quantity of the commodity produced by the electricity sector at location l - season p and load block b by the production technology t
$P_{ey,l,p,b,t}^{S_GEN_tech}$	Price of commodity produced by the electricity sector at location l - season p and load block b by the production technology t (without foreign aggregations and production taxes)
$Q_{ey,l,p,b}^{S_GEN}$	Quantity of the commodity produced by the electricity sector at location l - season p and load block b
$P_{ey,l,p,b}^{S_GEN}$	Price of commodity produced by the electricity sector at location l - season p and load block b (without foreign aggregations and production taxes)
$Q_{ey,l,p,b}^{D_GEN}$	Quantity of aggregated imported and domestic produced supply of electricity good at location l - season p and load block b
$P_{ey,l,p,b}^{D_GEN}$	Price of aggregated electricity good at location l - season p and load block b
$Q_{ey,l,p,b}^{Q_GEN}$	Quantity of final domestic market supply of electricity good at location l - season p and load block b
$P_{ey,l,p,b}^{Q_GEN}$	Price of final domestic electricity good at location l - season p and load block b
<u>Imports:</u>	
$Q_{ey,l,p,b}^{M_GEN}$	Quantity of good electricity imported from the exterior
$P_{ey,l,p,b}^{M_GEN}$	Price of imported electricity
<u>Exports:</u>	
$Q_{ey,l,p,b}^{EX_GEN}$	Quantity of good electricity imported from the exterior
$P_{ey,l,p,b}^{EX_GEN}$	Price of imported electricity
<u>Government:</u>	
Y_{ey}^G	Total government income
E_{ey}^G	Total government expenditure
Y_{ey}^{TAX}	Total government taxes income
<u>Savings and Investments</u>	
S_{ey}	Total economy savings
S_{ey}^H	Households savings
S_{ey}^G	Government savings
S_{ey}^{Ext}	Foreign total savings

I_{ey}	Total investment
$Q_{ey,gne}^I$	Quantity of non-electricity good gne demanded as investment good (electricity cannot be an investment good because it cannot be stored, at least in its commodity form)

Equations:

Household behavior:

$$Q_{ey,gne}^H = \frac{\bar{c}_{ey,gne}^H (1 - \bar{s}_{ey}^H) Y_{ey}^H}{(1 + \bar{t}\bar{x}_{ey}^H) P_{ey,gne}^Q}, \forall ey, gne$$

$$Q_{ey,l,p,b}^{H_GEN} = \frac{\bar{c}_{ey,l,p,b}^{H_GEN} (1 - \bar{s}_{ey}^H) Y_{ey}^H}{(1 + \bar{t}\bar{x}_{ey}^H) P_{ey,l,p,b}^{Q_GEN}}, \forall ey, l, p, b$$

$$Q_{ey}^{H_TDeO} = \frac{\bar{c}_{ey}^{H_TDeO} (1 - \bar{s}_{ey}^H) Y_{ey}^H}{(1 + \bar{t}\bar{x}_{ey}^H) P_{ey}^{H_TDeO}}, \forall ey$$

$$Y_{ey}^H = \sum_{pf} P_{ey,pf} \bar{q}_{ey,pf}^H + \overline{transf}_{ey}^{G-H}$$

$$+ \overline{pSc}_{ey}^H \left(\sum_{sne} \bar{t}\bar{x}_{ey,sne,pf=Labor}^{SC_SNE} P_{ey,pf=Labor} Q_{ey,pf=Labor,sne}^{pf_SNE} \right.$$

$$+ \bar{t}\bar{x}_{ey,pf=Labor}^{SC_TDeO} P_{ey,pf=Labor} Q_{ey,pf=Labor}^{pf_TDeO}$$

$$\left. + \sum_{l,p,b,t} \bar{t}\bar{x}_{ey,l,p,b,t,pf=Labor}^{SC_GEN} P_{ey,pf=Labor} Q_{ey,pf=Labor,l,p,b,t}^{pf_GEN_tech} \right) + \overline{transf}_{ey}^{Ext-H}, \forall ey$$

$$S_{ey}^H = \bar{s}_{ey}^H Y_{ey}^H, \forall ey$$

Non electricity production sector:

$$(Q_{ey,pf=Labor,sne}^{pf_SNE})^{\frac{1}{\sigma_{sne}^{VA}}} (1 - \bar{a}_{sne}^{VA}) \left((1 + \bar{t}\bar{x}_{ey,sne,pf=Labor}^{SC_SNE}) P_{ey,pf=labor} \right)$$

$$= (Q_{ey,pf=Capital,sne}^{pf_SNE})^{\frac{1}{\sigma_{sne}^{VA}}} (\bar{a}_{sne}^{VA}) (P_{ey,pf=Capital}), \forall ey, sne$$

$$CES(Q_{ey,pf,sne}) - Q_{ey,sne}^{VA} = 0 \quad \perp \quad p_{ey,sne}^{VA}, \forall ey, sne$$

$$P_{ey,sne}^{VA} Q_{ey,sne}^{VA} = (1 + \bar{t}\bar{x}_{ey,sne}^{SC_SNE}) P_{ey,pf=Labor} Q_{ey,pf=Labor,sne}^{pf_SNE}$$

$$+ P_{ey,pf=Capital} Q_{ey,pf=Capital,sne}^{pf_SNE}, \forall ey, sne$$

$$Q_{ey,sne}^S = \frac{Q_{ey,gne,sne}^H}{\bar{c}_{ey,gne,sne}^H} \quad \perp \quad Q_{ey,gne,sne}^H, \forall ey, gne, sne$$

$$Q_{ey,sne}^S = \frac{Q_{ey,l,dp,db,sne}^{II_GEN_SNE}}{\bar{c}_{ey,l,dp,db,sne}^{II_GEN_sne}} \perp Q_{ey,l,dp,db,sne}^{II_GEN_SNE}, \forall ey, l, dp, db, sne$$

$$Q_{ey,sne}^S = \frac{Q_{ey,sne}^{II_TDeO_SNE}}{\bar{c}_{ey,sne}^{II_TDeO_sne}} \perp Q_{ey,sne}^{II_TDeO_SNE}, \forall ey, sne$$

$$Q_{ey,sne}^S = \frac{Q_{ey,sne}^{VA}}{\bar{c}_{ey,sne}^{VA}} \perp Q_{ey,sne}^{VA}, \forall ey, sne$$

$$\begin{aligned} P_{ey,sne}^S Q_{ey,sne}^S + \overline{transf}_{ey,sne}^{G,sne} - P_{ey,sne}^{VA} Q_{ey,sne}^{VA} - \sum_{gne} (1 + \bar{t}x_{ey,sne}^{Pdct}) P_{ey,gne}^Q Q_{ey,gne}^{II} \\ - (1 + \bar{t}x_{ey,sne}^{Pdct}) P_{ey}^{QTDeO} Q_{ey,sne}^{II_TDeO_SNE} - \sum_{l,p,b} (1 + \bar{t}x_{ey,sne}^{Pdct}) P_{ey,l,p,b}^{QGEN} Q_{ey,l,p,b}^{II_GEN_SNE} \\ - \overline{emiss\ rate}_{ey,sne}^{CO2} \bar{p}_{ey}^{CO2} Q_{ey,sne}^S \leq 0 \perp Q_{ey,sne}^S \geq 0, \forall ey, sne \end{aligned}$$

Imports Armington Aggregation:

$$(Q_{ey,gne}^S)^{\frac{1}{\bar{\sigma}_{sne}^{VA}}} (1 - \bar{a}_{gne}^D) \left((1 + \bar{t}x_{ey,sne}^{Pdct}) P_{ey,gne}^S \right) = (Q_{ey,gne}^M)^{\frac{1}{\bar{\sigma}_{sne}^{VA}}} (\bar{a}_{gne}^D) (\bar{p}_{ey,gne}^M), \forall ey, gne$$

$$Q_{ey,gne}^D - CES(Q_{ey,gne}^S, Q_{ey,gne}^M) = 0 \perp \lambda_{ey,gne}^D, \forall ey, gne$$

$$P_{ey,gne}^D Q_{ey,gne}^D - (1 + \bar{t}x_{ey,gne}^{Pdct}) P_{ey,gne}^S Q_{ey,gne}^S - \bar{p}_{ey,gne}^M Q_{ey,gne}^M = 0, \forall ey, gne$$

Exports CET disaggregation:

$$(\bar{b}_{gne}^Q)^{\bar{\sigma}_{gne}^Q} \left((1 + \bar{t}x_{ey,Exp}^{Pdct}) \bar{p}_{ey,gne}^{EX} \right)^{\bar{\sigma}_{gne}^Q} Q_{ey,gne}^Q = (1 - \bar{b}_{gne}^Q)^{\bar{\sigma}_{gne}^Q} (P_{ey,gne}^Q)^{\bar{\sigma}_{gne}^Q} Q_{ey,gne}^{EX}, \forall ey, gne$$

$$Q_{ey,gne}^D - CET(Q_{ey,gne}^Q, Q_{ey,gne}^{EX}) = 0 \perp \lambda_{ey,gne}^Q, \forall ey, gne$$

$$P_{ey,gne}^Q Q_{ey,gne}^Q + \bar{p}_{ey,gne}^{EX} Q_{ey,gne}^{EX} - P_{ey,gne}^D Q_{ey,gne}^D = 0, \forall ey, gne$$

Transmission, distribution and other electricity services:

$$Q_{ey}^{VA_TDeO} = \frac{Q_{ey,pf}^{pf_TDeO}}{\bar{c}_{ey,pf}^{pf_TDeO}} \perp Q_{ey,pf}^{pf_TDeO}, \forall ey, pf$$

$$P_{ey}^{VA_TDeO} Q_{ey}^{VA_TDeO} = (1 + \bar{t}x_{ey}^{SC_TDeO}) P_{ey,pf=Labor} Q_{ey,pf=Labor}^{pf_TDeO} + P_{ey,pf=Capital} Q_{ey,pf=Capital}^{pf_TDeO}, \forall ey$$

$$Q_{ey}^{S_TDeO} = \frac{Q_{ey,gne}^{II_GNE_TDeO}}{\bar{c}_{ey,gne}^{II_gne_TDeO}} \perp Q_{ey,gne}^{II_GNE_TDeO}, \forall ey, gne$$

$$Q_{ey}^{S_TDeO} = \frac{Q_{ey,l,dp,db}^{II_GEN_TDeO}}{\bar{c}_{ey,l,dp,db}^{II_GEN_TDeO}} \perp Q_{ey,l,dp,db}^{II_GEN_TDeO}, \forall ey, l, dp, db$$

$$Q_{ey}^{S_TDeO} = \frac{Q_{ey}^{II_TDeO_TDeO}}{\bar{c}_{ey}^{II_TDeO_TDeO}} \perp Q_{ey}^{II_TDeO_TDeO} \quad , \forall ey$$

$$Q_{ey}^{S_TDeO} = \frac{Q_{ey}^{VA_TDeO}}{\bar{c}_{ey}^{VA_TDeO}} \perp Q_{ey}^{VA_TDeO} \quad , \forall ey$$

$$\begin{aligned} P_{ey}^{S_TDeO} Q_{ey}^{S_TDeO} + \overline{transf}_{ey}^{G-TDeO} - P_{ey}^{VA_TDeO} Q_{ey}^{VA_TDeO} - \sum_{gne} (1 + \bar{t}x_{ey}^{Pdct_TDeO}) P_{ey,gne}^Q Q_{ey,gne}^{II_GNE_TDeO} \\ - (1 + \bar{t}x_{ey}^{Pdct_TDeO}) P_{ey}^Q Q_{ey}^{II_TDeO_TDeO} \\ - \sum_{l,dp,db} (1 + \bar{t}x_{ey}^{Pdct_TDeO}) P_{ey,l,dp,db}^Q Q_{ey,l,dp,db}^{II_GEN_TDeO} - \overline{emiss\ rate}_{ey}^{CO2_TDeO} \bar{p}_{ey}^{CO2} Q_{ey}^{S_TDeO} \\ \leq 0 \perp Q_{ey}^{S_TDeO} \geq 0 \quad , \forall ey \end{aligned}$$

$$Q_{ey}^{D_TDeO} = Q_{ey}^{S_TDeO} \quad , \forall ey$$

$$P_{ey}^{D_TDeO} Q_{ey}^{D_TDeO} = (1 + \bar{t}x_{ey}^{Pdction_TDeO}) (P_{ey}^{S_TDeO} Q_{ey}^{S_TDeO}) \quad , \forall ey$$

$$Q_{ey}^Q = Q_{ey}^{D_TDeO} \quad , \forall ey$$

$$P_{ey}^Q Q_{ey}^Q = P_{ey}^{D_TDeO} Q_{ey}^{D_TDeO} \quad , \forall ey$$

Generation Electricity sector:

$$Q_{ey,l,p,b,t}^{VA_GEN_tech} = \frac{Q_{ey,pf,l,p,b,t}^{pf_GEN_tech}}{\bar{c}_{pf,l,gp,gb,t}^{pf_GEN_tech}} \perp Q_{ey,pf,l,p,b,t}^{pf_GEN_tech} \quad , \forall ey, pf, l, gp, gb, t$$

$$P_{ey,l,p,b,t}^{VA_GEN_tech} Q_{ey,l,p,b,t}^{VA_GEN_tech} = \sum_{pf} (1 + \bar{t}x_{l,gp,gb,t}^{SC_GEN}) P_{ey,pf} Q_{ey,pf,l,p,b,t}^{pf_GEN_tech} \quad , \forall ey, l, gp, gb, t$$

$$Q_{ey,l,p,b,t}^{S_GEN_tech} = \frac{Q_{ey,gne,l,p,b,t}^{II_GNE_GEN_tech}}{\bar{c}_{gne,l,gp,gb,t}^{II_GNE_GEN_tech}} \quad , \forall ey, gne, l, gp, gb, t$$

$$Q_{ey,l,p,b,t}^{S_GEN_tech} = \frac{Q_{ey,l,dp,db,gp,gb,t}^{II_GEN_GEN_tech}}{\bar{c}_{l,dp,db,gp,gb,t}^{II_GEN_GEN_tech}} \quad , \forall ey, l, dp, db, gp, gb, t$$

$$Q_{ey,l,p,b,t}^{S_GEN_tech} = \frac{Q_{ey,l,p,b,t}^{II_TDeO_GEN_tech}}{\bar{c}_{l,p,b,t}^{II_TDeO_GEN_tech}} \quad , \forall ey, l, p, b, t$$

$$Q_{ey,l,p,b,t}^{S_GEN_tech} = \frac{Q_{ey,l,p,b,t}^{VA_GEN_tech}}{\bar{c}_{l,p,b,t}^{VA_GEN_tech}} \quad , \forall ey, l, p, b, t$$

$$\begin{aligned}
& P_{ey,l,p,b,t}^{S_GEN_tech} Q_{ey,l,p,b,t}^{S_GEN_tech} - P_{ey,l,gp,gb,t}^{VA_GEN_tech} Q_{ey,l,p,b,t}^{VA_GEN_tech} + \sum_{gne} (1 + \bar{t}x_{l,gp,gb,t}^{Pdct_GEN}) P_{ey,gne}^Q Q_{ey,gne,l,gp,gb,t}^{II_GNE_GEN_tech} \\
& + (1 + \bar{t}x_{l,gp,gb,t}^{Pdct_GEN}) P_{ey}^{Q_TDeO} Q_{ey,l,p,b,t}^{II_TDeO_GEN_tech} \\
& + \sum_{dp,db} (1 + \bar{t}x_{l,gp,gb,t}^{Pdct_GEN}) P_{ey,l,dp,db}^{Q_GEN} Q_{ey,l,dp,db,gp,gb,t}^{II_GEN_GEN_tech} \\
& + \overline{emiss\ rate}_{l,gp,gb,t}^{CO2} \bar{p}^{CO2} Q_{ey,l,gp,gb,t}^{S_GEN_tech} \leq 0 \perp Q_{ey,l,gp,gb,t}^{S_GEN_tech} \geq 0, \forall ey, l, gp, gb
\end{aligned}$$

$$Q_{ey,l,gp,gb}^{S_GEN} = \frac{Q_{ey,l,gp,gb,t}^{S_GEN_tech}}{\bar{c}_{l,p,b,t}^{ii_tech_GEN}}, \forall ey, l, gp, gb$$

$$P_{ey,l,gp,gb}^{S_GEN} Q_{ey,l,gp,gb}^{S_GEN} = \left(\sum_t P_{ey,l,gp,gb,t}^{S_GEN_tech} Q_{ey,l,gp,gb,t}^{S_GEN_tech} \right) - \sum_t \overline{emiss_allow}_{ey,t,l,gp,gb}, \forall ey, l, gp, gb$$

$$Q_{ey,l,gp,gb}^{D_GEN} = Q_{ey,l,gp,gb}^{S_GEN} + \bar{q}_{ey,l,gp,gb}^{M_GEN}, \forall ey, l, gp, gb$$

$$P_{ey,l,gp,gb}^{D_GEN} Q_{ey,l,gp,gb}^{D_GEN} = (1 + \bar{t}x_{l,gp,gb}^{Pdct_GEN}) P_{ey,l,gp,gb}^{S_GEN} Q_{ey,l,gp,gb}^{S_GEN} + \bar{p}_{ey,l,gp,gb}^{M_elect} \bar{q}_{ey,l,gp,gb}^{M_elect}, \forall ey, l, gp, gb$$

$$Q_{ey,l,gp,gb}^{Q_GEN} = Q_{ey,l,gp,gb}^{D_GEN} - \bar{q}_{ey,l,gp,gb}^{EX_GEN}, \forall ey, l, gp, gb$$

$$P_{ey,l,gp,gb}^{Q_GEN} Q_{ey,l,gp,gb}^{Q_GEN} = P_{ey,l,gp,gb}^{D_GEN} Q_{ey,l,gp,gb}^{D_GEN} - \bar{p}_{ey,l,gp,gb}^{EX_GEN} \bar{q}_{ey,l,gp,gb}^{EX_GEN}, \forall ey, l, gp, gb$$

$$P_{ey,l,gp,gb}^{Q_GEN} Q_{ey,l,gp,gb}^{Q_GEN}$$

$$= P_{ey,l,gp,gb}^{D_GEN} Q_{ey,l,gp,gb}^{D_GEN} - \bar{p}_{ey,l,gp,gb}^{EX_GEN} \bar{q}_{ey,l,gp,gb}^{EX_GEN} + \overline{mkt_surplus}_{ey,l,gp,gb}, \forall ey, l, gp, gb$$

Government:

$$Y_{ey}^G = \sum_{pf} P_{ey,pf} \bar{q}_{ey,pf}^G + \overline{transf}_{ey}^{Ext-G} + Y_{ey}^{TAX}, \forall ey$$

$$E_{ey}^G = \sum_{gne} (1 + \bar{t}x_{ey}^G) P_{ey,gne}^Q \bar{q}_{ey,gne}^G + (1 + \bar{t}x_{ey}^G) P_{ey}^{Q_TDeO} \bar{q}_{ey}^{G_TDeO} + \sum_{l,p,b} (1 + \bar{t}x_{ey}^G) P_{ey,l,p,b}^{Q_GEN} \bar{q}_{ey,l,p,b}^{G_GEN}$$

$$+ \overline{transf}_{ey}^{G-H}$$

$$+ \overline{psc}_{ey}^H \left(\sum_{sne} \bar{t}x_{ey,sne,pf=Labor}^{SC_SNE} P_{ey,pf=Labor} Q_{ey,pf=Labor,sne}^{pf_SNE} \right)$$

$$+ \bar{t}x_{ey,pf=Labor}^{SC_TDeO} P_{ey,pf=Labor} Q_{ey,pf=Labor}^{pf_TDeO}$$

$$+ \sum_{l,p,b,t} \bar{t}x_{ey,l,p,b,t,pf=Labor}^{SC_GEN} P_{ey,pf=Labor} Q_{ey,pf=Labor,l,p,b,t}^{pf_GEN_tech} \Big) + \sum_{sne} \overline{transf}_{ey,sne}^{G_sne}$$

$$+ \sum_{l,gp,gb} \overline{transf}_{ey,l,gp,gb}^{G_GEN} + \overline{transf}_{ey}^{G_TDeO}, \forall ey$$

$$Y_{ey}^G - E_{ey}^G = S_{ey}^G, \forall ey$$

$$\begin{aligned}
Y_{ey}^{TAX} = & \sum_{sne} \bar{t}x_{ey,sne}^{SC,SNE} P_{ey,pf=Labor} Q_{ey,pf=Labor,sne}^{pf,SNE} + \bar{t}x_{ey,sne}^{SC,TDeO} P_{ey,pf=Labor} Q_{ey,pf=Labor}^{pf,TDeO} \\
& + \sum_{l,p,b,t} \bar{t}x_{l,p,b,t}^{SC,GEN} P_{ey,pf=Labor} Q_{ey,pf=Labor,l,p,b,t}^{pf,tech} + \sum_{sne,gne} \bar{t}x_{sne}^{Pdct} P_{ey,gne}^Q Q_{ey,gne}^{II} \\
& + \sum_{gne} \bar{t}x_{Pdct_TDeO} P_{ey,gne}^Q Q_{ey,gne}^{II_GNE_TDeO} + \sum_{sne} \bar{t}x_{sne}^{Pdct} P_{ey}^{Q_TDeO} Q_{ey,sne}^{II_TDeO_SNE} \\
& + \sum_{l,p,b,t,gne} \bar{t}x_{l,p,b,t}^{Pdct_GEN} P_{ey,gne}^Q Q_{ey,gne,l,p,b,t}^{II_GNE_GEN_tech} + \sum_{sne} \bar{t}x_{sne}^{Pdct} P_{ey}^{Q_TDeO} Q_{ey,sne}^{II_TDeO_SNE} \\
& + \bar{t}x_{Pdct_TDeO} P_{ey}^{Q_TDeO} Q_{ey}^{II_TDeO_TDeO} + \sum_{l,p,b,t} \bar{t}x_{l,p,b,t}^{Pdct_GEN} P_{ey}^{Q_TDeO} Q_{ey,l,p,b,t}^{II_TDeO_GEN_tech} \\
& + \sum_{sne,l,p,b} \bar{t}x_{sne}^{Pdct} P_{ey,l,p,b}^{Q_GEN} Q_{ey,l,p,b,sne}^{II_GEN_SNE} + \sum_{l,dp,db} \bar{t}x_{Pdct_TDeO} P_{ey,l,dp,db}^{Q_GEN} Q_{ey,l,dp,db}^{II_GEN_TDeO} \\
& + \sum_{l,gb,t,dp,db} \bar{t}x_{l,gb,t}^{Pdct_GEN} P_{ey,l,dp,db}^{Q_GEN} Q_{ey,l,dp,db,gb,t}^{II_GEN_GEN_tech} + \sum_{sne} \bar{t}x_{sne}^{Pdct} P_{ey,sne}^S Q_{ey,sne}^S \\
& + \bar{t}x_{Pdct_TDeO} P_{ey}^{S_TDeO} Q_{ey}^{S_TDeO} + \sum_{l,p,b} \bar{t}x_{l,gb,gb}^{Pdct_GEN} P_{ey,l,gb,gb}^{S_GEN} Q_{ey,l,gb,gb}^{S_GEN} \\
& + \sum_{gne} \bar{t}x_{Exp}^{Pdct=EX} P_{ey,gne}^{EX} Q_{ey,gne}^{EX} + \sum_{l,p,b} \bar{t}x_{Exp}^{Pdct=EX_GEN} P_{ey,l,gb,gb}^{EX_GEN} \bar{q}_{ey,l,gb,gb}^{EX_GEN} + \sum_{gne} \bar{t}x_{Exp}^{HP} P_{ey,gne}^Q Q_{ey,gne}^H \\
& + \sum_{l,p,b} \bar{t}x_{HP} P_{ey,l,p,b}^{Q_GEN} Q_{ey,l,p,b}^H + \bar{t}x_{HP} P_{ey}^{H_TDeO} Q_{ey}^{H_TDeO} + \sum_{gne} \bar{t}x_{G} P_{ey,gne}^Q \bar{q}_{ey,gne}^G \\
& + \bar{t}x_{G} P_{ey}^{Q_TDeO} \bar{q}_{ey}^{G_TDeO} + \sum_{l,p,b} \bar{t}x_{G} P_{ey,l,p,b}^{Q_GEN} \bar{q}_{ey,l,p,b}^{G_GEN} + \sum_{gne} \bar{t}x_{Inv} P_{ey,gne}^Q Q_{ey,gne}^I \\
& + \sum_{sne} \overline{emiss\ rate}_{sne}^{CO2} \bar{p}_{ey}^{CO2} Q_{ey,sne}^S + \overline{emiss\ rate}^{CO2_TDeO} \bar{p}_{ey}^{CO2} Q_{ey}^{S_TDeO} \\
& + \sum_{l,p,b,t} \overline{emiss\ rate}_{l,gb,gb,t}^{CO2} \bar{p}_{ey}^{CO2} Q_{ey,l,gb,gb,t}^{S_GEN_tech}
\end{aligned}$$

Savings and Investments:

$$\begin{aligned}
S_{ey} &= S_{ey}^H + S_{ey}^G + S_{ey}^{Ext} + \overline{transf}_{ey}^{Ext,K} \quad , \forall ey \\
S_{ey}^{Ext} &= \sum_{gne} \bar{p}_{ey,gne}^M Q_{ey,gne}^M + \sum_{l,gb,gb} \bar{p}_{ey,l,gb,gb}^{M_elect} \bar{q}_{ey,l,gb,gb}^{M_elect} - \sum_{gne} (1 + \bar{t}x_{ey,Exp}^{Pdct}) \bar{p}_{ey,gne}^{EX} Q_{ey,gne}^{EX} \\
& - \sum_{l,gb,gb} (1 + \bar{t}x_{ey,Exp}^{Pdct}) \bar{p}_{ey,l,gb,gb}^{EX_elect} \bar{q}_{ey,l,gb,gb}^{EX_elect} - \overline{transf}_{ey}^{Ext-G} - \overline{transf}_{ey}^{Ext-H} \\
& - \overline{transf}_{ey}^{Ext-K} \quad , \forall ey \\
Q_{ey,gne}^I &= \frac{\bar{\theta}_{ey,gne}}{(1 + \bar{t}x_{ey}^{Inv}) P_{ey,gne}^Q} I_{ey} \quad , \forall ey, gne
\end{aligned}$$

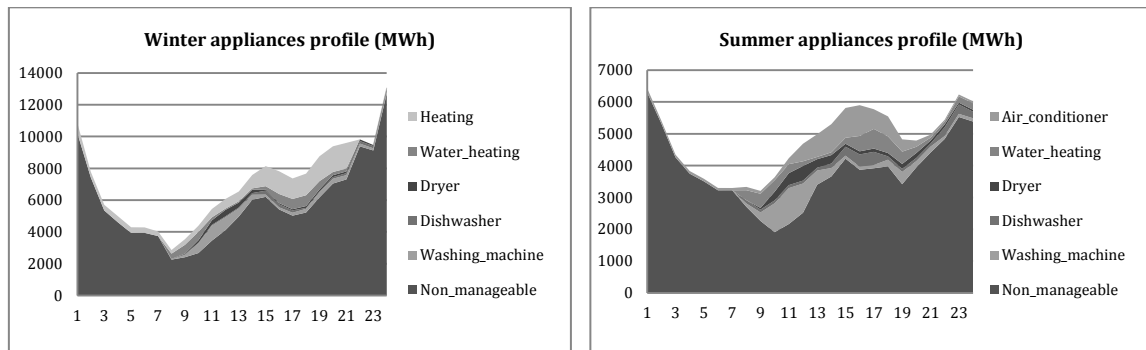
Market clearing conditions:

$$\begin{aligned}
& \sum_{sne} Q_{ey,pf,sne} + Q_{ey,pf}^{pf_TDeO} + \sum_{l,gp,gb,t} Q_{ey,pf,l,gp,gb,t}^{pf_tech} \leq \bar{q}_{ey,pf}^H + \bar{q}_{ey,pf}^G \perp P_{ey,pf}, \forall ey, pf \\
Q_{ey,gne}^H + \bar{q}_{ey,gne}^G + \sum_{sne} Q_{ey,gne,sne}^{II} + Q_{ey,gne}^{II_GNE_TDeO} + \sum_{l,p,b,t} Q_{ey,gne,l,p,b,t}^{II_GNE_GEN_tech} + Q_{ey,gne}^I & \leq Q_{ey,gne}^Q \\
& \perp P_{ey,gne}^Q, \forall ey, gne \\
Q_{ey,l,p,b}^{H_GEN} + \bar{q}_{ey,l,p,b}^{G_elec} + \sum_{sne} Q_{ey,l,p,b,sne}^{II_GEN_SNE} + Q_{ey,l,p,b}^{II_GEN_TDeO} + \sum_{gp,gb,t} Q_{ey,l,p,b,gp,gb,t}^{II_GEN_GEN_tech} & \leq Q_{ey,l,p,b}^{QGEN} \\
& \perp P_{ey,l,p,b}^{QGEN}, \forall ey, l, p, b \\
Q_{ey}^{H_TDeO} + \bar{q}_{ey}^{G_TDeO} + \sum_{sne} Q_{ey,sne}^{II_TDeO_SNE} + Q_{ey}^{II_TDeO_TDeO} + \sum_{l,p,b,t} Q_{ey,l,p,b,t}^{II_TDeO_GEN_tech} & \leq Q_{ey}^{Q_TDeO} \\
& \perp P_{ey}^{Q_TDeO}, \forall ey \\
& I_{ey} = S_{ey}, \forall ey
\end{aligned}$$

Annex II – Demand Response Policy Assessment

The potential DR shiftable and reduced loads are estimated from the availability and technical characteristics of Spanish households' appliances. The equations used on the estimations of both bottom-up and top-down policy consequences are described below. Figure 3 summarizes the average manageable load considered at each hour of the day, and Table 7 describes the load reduction potential from using more economic or efficient modes on the appliances evaluated.

Figure 3. Manageable Appliance Load.



Source: own elaboration.

Table 7. Appliance Conservation Potential.

	Appliances					
	Washing Machine	Dishwasher	Dryer	Water Heating	Heating	Air Conditioner
Conservation Potential	0,4%	0,4%	0,2%	0,3%	0,5%	0,5%

Source: own elaboration.

Parameters:

$\overline{\text{displaceable_load}}_{y,l,p,b}$	Demand response displaceable load
$\overline{\text{conservable_load}}_{y,l,p,b}$	Demand response conservable load
$\overline{\text{gad_price}}_{y,l,p,b}$	Initial electricity base price
$\overline{\text{dur}}_{l,p,b}$	load block duration (hours)
$\overline{\text{min_sav}}$	Minimum savings required to make the demand displacement

Variables:

INCREASED_DR_LOAD	Increased demand in load block due to demand response displacement (MW)
$\text{DECREASED_DR_LOAD}_{y,l,p,b}$	Decreased demand in load block due to demand response displacement (MW)
$\text{CONSERVED_DR_LOAD}_{y,l,p,b}$	Conserved demand in load block due to demand response

displacement (MW)

Equations:

Active demand response demand balance:

$$\begin{aligned}
& \overline{\text{demand}}_{y,l,p,b} + INCREASED_DR_LOAD_{y,l,p,b} - DECREASED_DR_LOAD_{y,l,p,b} \\
& - CONSERVED_DR_LOAD_{y,l,p,b} \\
& \leq \sum_{t,f} PGEN_{y,t,f,l,p,b} + \overline{\text{pimp}}_{y,l,p,b} - PPUMPED_{y,l,p,b} - (\overline{\text{own_cons}}) \sum_{t,f} PGEN_{y,t,f,l,p,b} \\
& - \overline{\text{loss}}_{y,l,p,b} \left(\sum_{t,f} PGEN_{y,t,f,l,p,b} + \overline{\text{pimp}}_{y,l,p,b} + \overline{\text{pexp}}_{y,l,p,b} - PPUMPED_{y,l,p,b} \right)
\end{aligned}$$

Maximum displacement:

$$DECREASED_DR_LOAD_{y,l,p,b} \leq \overline{\text{displaceable_load}}_{y,l,p,b}$$

Displacement balance:

$$\sum_b (INCREASED_DR_LOAD_{y,l,p,b} \overline{\text{dur}}_{l,p,b}) = \sum_b (DECREASED_DR_LOAD_{y,l,p,b} \overline{\text{dur}}_{l,p,b})$$

Potency conservation limit:

$$CONSERVED_DR_LOAD_{y,l,p,b} \leq \overline{\text{conservable_load}}_{y,l,p,b}$$

Minimal savings requirement:

$$\begin{aligned}
& \sum_b (DECREASED_DR_LOAD_{y,l,p,b} \overline{\text{gad_price}}_{y,l,p,b} \overline{\text{dur}}_{l,p,b}) \\
& - \sum_b (INCREASED_DR_LOAD_{y,l,p,b} \overline{\text{gad_price}}_{y,l,p,b} \overline{\text{dur}}_{l,p,b}) \\
& \leq (1 - \overline{\text{min_sav}}) \sum_b (\overline{\text{displaceable_load}}_{y,l,p,b} \overline{\text{gad_price}}_{y,l,p,b} \overline{\text{dur}}_{l,p,b})
\end{aligned}$$