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

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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 the second of two parts and focuses on the CGE model applied to the evaluation of an energy policy with temporal consequences.

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

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

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1 Introduction

Policies that affect the way in which we produce or consume electricity are expected to become more popular and also more intense in a context of increasing concerns for climate change, energy security or economic competitiveness, as shown for example in Europe (European Comission, 2011). Many of these policies will change not only the amount of electricity produced or consumed, but also the time at which this is done. A good example of this is demand response programs, currently being implemented or considered in many regions of the US and Europe (e.g., Faruqui & Sergici, 2010).

Demand response programs try to correct a very significant market failure in electricity markets, the fact that consumers do not receive perfect information on the time-varying cost of the electricity they consume, and therefore cannot adjust their hourly consumption accordingly[3]. The advances in communication and metering technologies (represented for example by the smart meter) have allowed for this market failure to be corrected, although at a cost: new infrastructures and devices need to be deployed for this to happen. Therefore, the benefits that correcting this market failure may entail regarding a more efficient electricity market need to be balanced against these costs.

Several attempts have been made at assessing the costs and benefits of these programs (see e.g. Conchado & Linares, 2012, for a review). However, most of them have used bottom-up, partial equilibrium approaches that only looked that costs and benefits for the power sector. These approaches are based on the assumption that the impact on the rest of the economy of the changes in the electricity sector will be negligible. But this assumption may not be valid any more. The increasing role that the electricity sector will arguably have in the future (see e.g. IEA, 2012) makes it more important than ever to account for the interactions between this sector and the rest of the economy when assessing the impact of electricity sector policies.

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[3] This is due to the combination of, on the one hand, the time-varying cost of producing electricity and the practical impossibility of storing it and on the other hand, the (up to now) lack of communication technologies that allowed to send this information to consumers and also to bill them on a time-varying basis.

In the case of demand response programs, the induced changes in electricity prices or in the use of generation technologies may affect significantly other sectors in the economy, mostly energy-related sectors, and this in turn may generate a non-negligible rebound effect. The correct assessment of these indirect or rebound effects requires a more detailed representation of the electricity sector in CGE models, so that, while retaining their characteristic evaluation of indirect effects, we may simulate correctly the load shifts and technological changes induced by demand response programs.

Although there have been some proposals for introducing electricity sector detail into CGE models (e.g. McFarland & Reilly, 2004, Paltsev et al., 2005 and Sue Wing, 2008), or even hybridizing bottom-up and top-down models (e.g. Böhringer & Rutherford, 2008 and Proença & St. Aubyn, 2012), the introduction of the time dimension in these models has not been addressed up to now. Part I of this paper (Rodrigues & Linares, 2013) presented the first attempt to our knowledge at building temporal disaggregation into a CGE framework, while keeping technological detail. In this companion paper we describe the CGE model developed, GEMED, and we show the application of the model to a realistic case study, the evaluation of a demand response program in Spain. Our results show clearly the benefits of this new approach: the larger the time detail of the representation of the electricity sector, the more realistic is the assessment of the indirect and rebound effects, and therefore, the better the evaluation of the policy effects.

Section 2 describes exhaustively the model, while section 3 shows the results for its application to the case in hand and highlights the clear advantages of using the GEMED model for the evaluation of the program. Section 4 presents some conclusions and research extensions.

2 The CGE model: GEMED

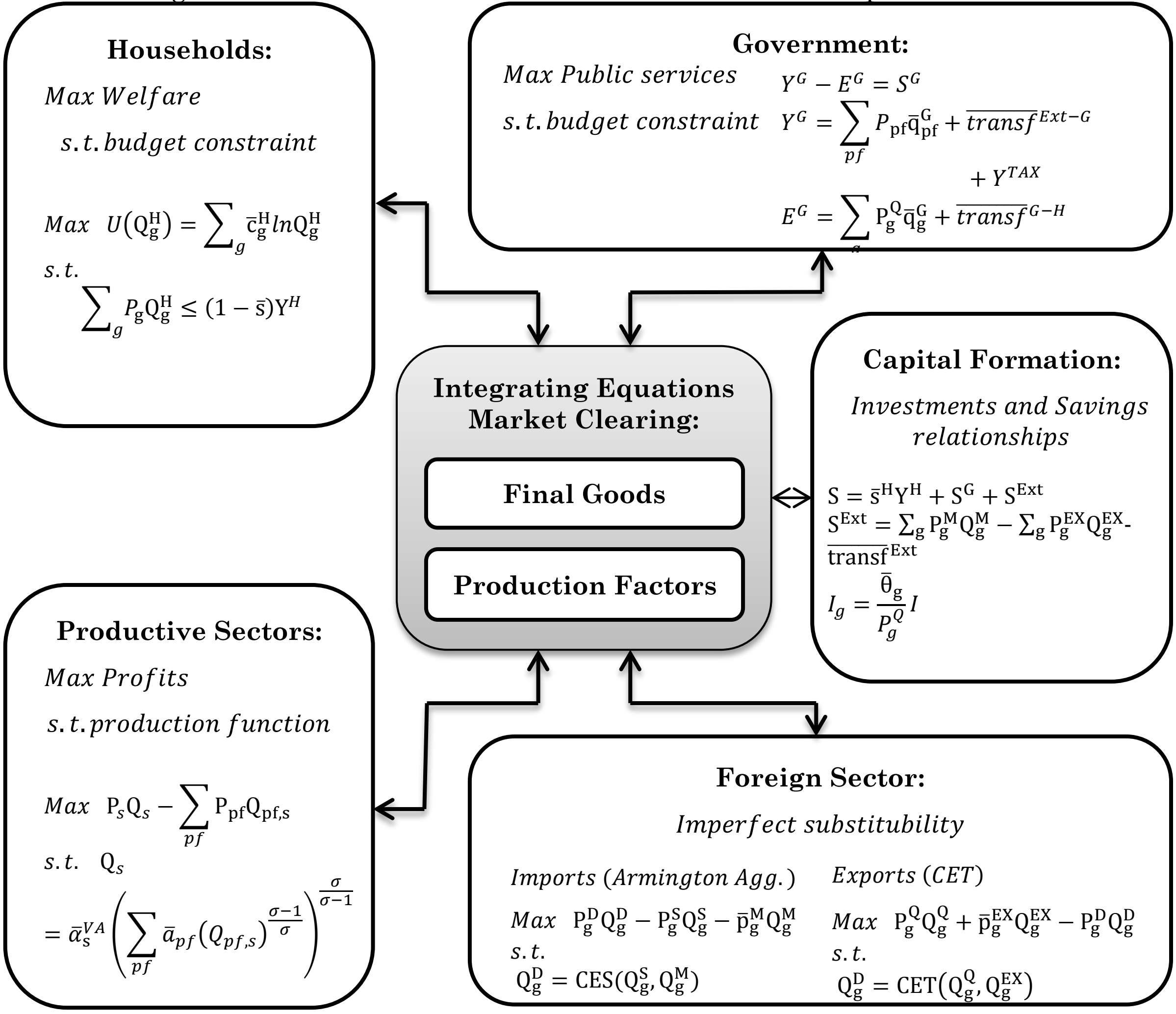
GEMED is a static, open economy, CGE model applied to a single country. The algebraic formulation follows a system of non-linear inequalities in the Arrow-Debreu general equilibrium framework. The model is implemented in GAMS and uses the PATH solver to obtain a local optimal equilibrium point.

The functional form 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 Appendix A.

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.

Figure 1. Schematic CGE model structure and main equations.



Source: own elaboration. The complete model and the notation can be found at Appendix A.

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. 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)[4] 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 composite good supplied is confronted with the external and internal demand for goods. The amount of goods directed to exports and the amount heading for the domestic market are determined using a constant elasticity of transformation function (CET). Finally, the remaining supply of domestic goods 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 endowment of production factors and the economic transfers received from the government and from overseas determine the available income for households 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). We assume an endogenous level of public savings and also that the government consumption is a fixed proportion of government

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[4] 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.

expenditure. The provision of public services does not follow these restrictive assumptions, but is aggregated in the services sectors and is modeled assuming factors' substitution and the use of intermediate inputs as described above for the productive sectors.

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.

The assumptions made in the model and described before are very much in line with the usual ones in CGE literature and small countries closure assumptions (e.g. Devarajan, Lewis, & Robinson, 1986; Robinson, Yu, Lewis, & Devarajan, 1999; Paltsev et al., 2005 and Proença & St. Aubyn, 2012).

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 generation and network components of electricity.

The network 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) description[5]. 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 generation/energy component (GEN) 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 homogeneity within the same period.

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[5] 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.

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 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 electricity production technologies whenever this production takes place in the same load block.

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.

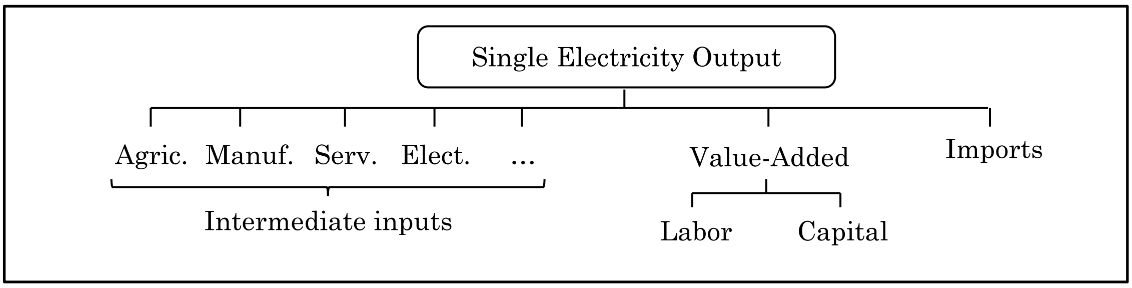


Figure 2b. Technology disaggregated electricity sector.

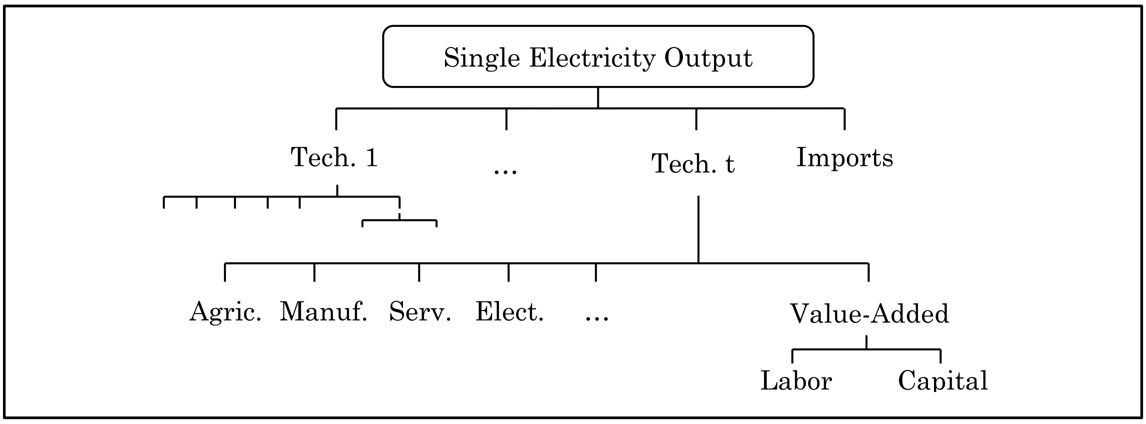
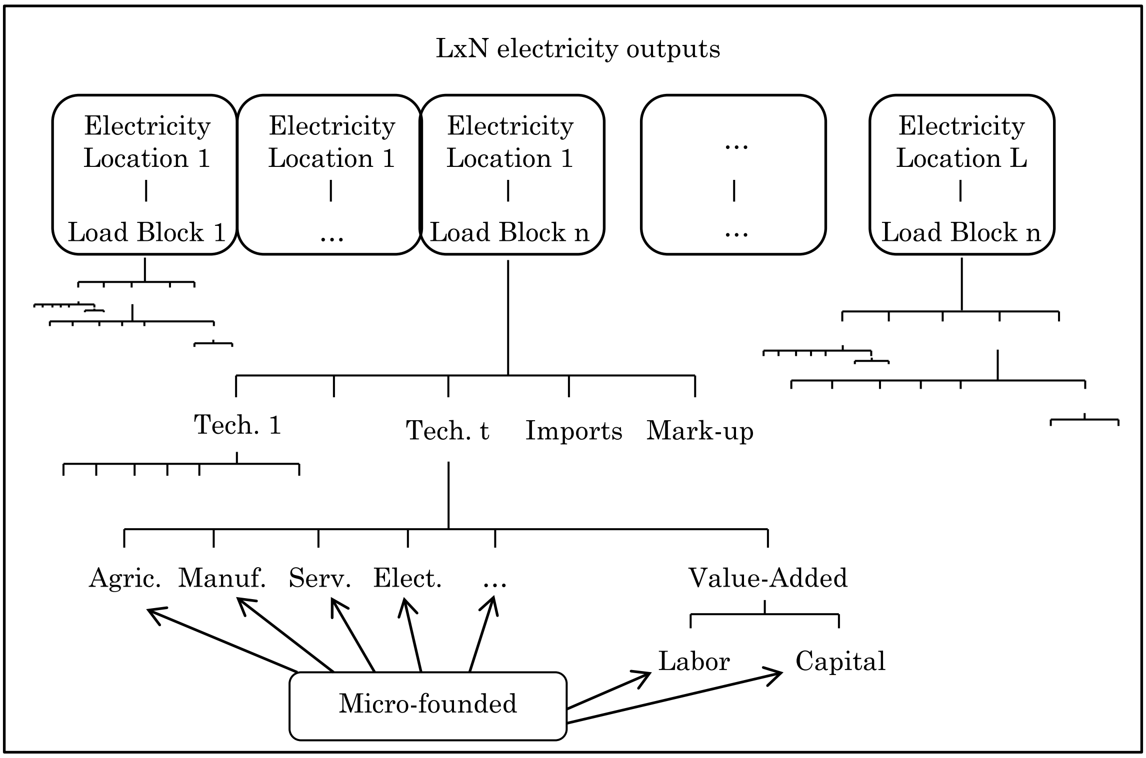


Figure 2c. GEMED electricity sector structure.



Source: own elaboration.

Besides the explicit representation of different electricity production technologies, the detailed arrangement proposed by the GEMED model differentiates the energy component according to the network location (*l* locations) [6] and, most particularly, by the time of consumption (*n* load blocks) [7]. The final GEN products are then represented by *n* times *l* dimensional vectors of prices and quantities, representing the production in different load blocks (*n*) and the demand decisions at different locations (*l*) (Figure 2c).

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

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[6] 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.

[7] 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 technology[8] has its own production function 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 existing network connections and historical electricity import profiles are used to exogenously determine the imported quantities at each load block.

However, 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 requires 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 mark-up 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).

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[8] 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 or 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, while at the same time addressing the time and location heterogeneity between different load blocks by the use of independent electricity products.

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 residential 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 to off-peak periods, and reducing loads across the board. This may also have effects on electricity prices, and therefore, on the electricity demand from other sectors, which in turn will feed back into the power system.

The model assumes for the sake of example, and without loss of generality, 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 Appendix B.

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 dataset[9].

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 in the paper.

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.

All data sources are publicly available and can be summarized in the table below (Table 2). Rodrigues and Linares (2013) presents in more detail the data necessary to define the CGE model and its calibration process.

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

Table 2. Data requirements summary.

Data type	Description	Source
Macroeconomic data	Social Accountability Matrix (Input-output tables and macroeconomic aggregates)	• Spanish National Institute of Statistics
	Elasticities (between production factors, imported and exported goods)	• Global Trade Analysis Project Spanish specific publications
Microeconomic technological data	Electricity demand profiles	• Spanish electricity system operator database (REE-ESIOS) • Spanish energy regulator, CNE • Spanish Electricity Demand Atlas, REE
	Electricity generation technologies (Construction time, life time, overnight costs, O&M costs, availability factors, thermodynamic efficiency, fuel prices, pollutant emissions, installed capacity,…)	• Spanish electricity system operator database (REE-ESIOS) • European Union Joint Research Centre reports • U.S. Energy Information Agency

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

Two assessments are have been made. First we compare the results of a demand response program under a bottom-up modeling perspective. The savings of an increase in demand response are estimated by allowing consumers to take additional shifting and conservation measures under our simulated scenario (see Appendix B for the DR simulation detailed equations).

Then, a second assessment is carried out under the general equilibrium approach. The results obtained allow to compare between both bottom-up and top-down alternatives and, more importantly, provide important evidence about the potential of considering a time differentiated model when assessing electricity policy consequences under a CGE framework.

In general terms, the global effect of the DR program in the economy is equivalent 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. Evaluating the bottom-up results, the DR program promotes savings from conservation and load shifts in the order of 2% of the electricity operation costs in the reference year[10] (see Table 3).

Table 3. Demand response policy BU results for the base year.

	Benchmark	**DR policy**	**Potential DR policy savings**		
	Total cost	**Total cost**	**Total savings**	**Conservation**	**Load shifting**
	(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, the closer to the real operation of the electricity sector is the simulation. The representation of a larger price variation between load blocks provides more incentives to consumers to conserve and shift in time their 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 direct benefits in terms of cost savings of the DR program for the power system.

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, as in e.g. Conchado & Linares, 2013, 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.

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[10] 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.

Therefore, we only summarize the main consequences of this policy and use the results to evaluate the different models presented in this paper[11].

A very important fact can be highlighted from the results in Table 3 to justify the use of load block disaggregation in a CGE evaluation of an electricity policy. Under a single load block assumption (LB_1 scenario) the policy evaluation behaves as under the usual technology-only disaggregated CGE. Because of the single electricity commodity formulation, this form is unable of evaluating endogenously the load shifts effects necessary for a correct evaluation of the benefits of DR programs (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 3.

In turn, 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 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 the DR program, and therefore the results of the program should be dampened in a general equilibrium context compared to the BU, which would overestimate them. As expected, the results of our model reflect exactly this behavior. The percentage of electricity demand reduction in the BU

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[11] 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 obtained from this work should be considered only as a lower bound approximation of the estimation of DR benefits. The electricity technologies aggregation level used (ten different technologies) flattens the peak behavior, therefore underestimating the benefits that could be achieved by an increase of the electricity demand flexibility.

model is larger than in the GEMED model in any of the load block disaggregation alternatives assessed (see the quantity column on Table 4) [12].

Table 4. Electricity generation sector results for the GEMED model and the BU model demand response evaluations.

	Price		**Quantity**		**Emissions**		**Final consumer savings**	
	BU	**GE**	**BU**	**GE**	**BU**	**GE**	**BU**	**GE**
	%	%	%	% **% dif.**	**% CO2e** **% Acid e**	**% CO2e** **% Acid e**	**10^6 €**	**10^6 €**
LB_1	0.00%	0.19%	-1.10%	-1.01% **-8.2%**	-1.11% -0.32%	-1.01% -1.01%	147.20	109.59
LB_6	-0.19%	0.20%	-1.16%	-1.07% **-8.3%**	-1.57% -0.55%	-0.98% -0.98%	215.26	138.07
LB_20	-0.64%	0.21%	-1.17%	-1.08% **-8.2%**	-1.59% -0.56%	-1.00% -1.00%	291.23	140.35
LB_45	-2.41%	0.22%	-1.28%	-1.13% **-11.2%**	-1.58% -0.53%	-0.81% -0.81%	578.16	144.41
LB_90	-2.29%	0.22%	-1.38%	-1.23% **-10.7%**	-1.71% -0.57%	-0.83% -0.83%	573.32	159.01
LB_180	-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 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) is 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 high as 11.2% and 10,7% when using the LB_45 and LB_90 scenario results.

In both models the potential for consumer savings from the DR program grows as the number of load blocks evaluated increases. This is reasonable because the more load blocks considered, the better the representation of electricity operation under

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[12] The absolute values of the TD GEMED and the BU models quantities and prices are not directly comparable because the models use 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.

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%). This different direction arises from the fact that the BU model is a cost minimization model whereas GEMED follows a fixed economy production function structure. Therefore a reduction in demand levels would mean a shift of the supply curve under the BU model, whereas the GEMED model would achieve a new equilibrium by moving along the production function curve.

The advantages of taking into account the load block disaggregation in the CGE modeling are much clearer if we compare the traditional CGE technological disaggregated results (the LB_1 scenario, Table 5), with the GEMED model results even with a small number of load blocks, as in scenario LB_6 (see Table 6).

Table 5. Typical CGE (GEMED DR_LB_1 scenario) simulation results.

		Prices		Quantities		Emissions
		Benchm.	**DR**	**Benchm.**	**DR**	
		p.u.	**p.u.** %	**p.u.**	**p.u.** %	**% CO2e** **% Acid e**
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 6. GEMED LB_6 scenario 2005 results.

				Prices		Quantities		Emissions
				Benchm.	**DR**	**Benchm.**	**DR**	
				p.u.	**p.u.** **%**	**p.u.**	**p.u.** **%**	**% CO2e** **% Acid e**
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 6, the introduction of time detail 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 in the traditional CGE), which allows for a much better representation in the model of the incentives for emission reductions or other sectors' peak-load reductions.

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 more closely the variation of final quantities under the policy scenario we can identify much better the advantages of having a time differentiation of the electricity commodity in the CGE model. The table below (Table 7) reproduces the variation in quantities of the previous tables, focusing on the differences between the load block disaggregated scenarios.

Table 7. Normalized differences of quantity effects between the electricity technology-only disaggregated CGE (LB_1) and the GEMED model (LB_6).

		Quantities		**Relative Difference**[(1)]
		LB_1	**LB_6**	$\left(Q_{LB\_6} - Q_{LB\_1}\right)\frac{Electricity}{Economy}$
		% Q_{LB_1}	% Q_{LB_6}	%
Products	**Electricity GEN**	-1.0133%	-1.07%	**-8,21%**
	Electricity TD&O	-0.0019%	-0.0088%	-1,08%
	Manufacturing	-0.0022%	-0.0040%	-0,28%
	Coal	-0.6711%	-0.6439%	**4,23%**
	Oil/Nuclear	0.0001%	-0.0048%	-0,76%
	Gas	-0.3748%	-0.4555%	**-12,60%**
	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 to what 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 7) that some sectors present much larger differences when we compare the results from the single (LB_1) and the six (LB_6) load blocks scenarios. The important fact to underline here is the concentration of changes in the electricity and fuel sectors.

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

As previously mentioned, DR programs incentivize the consumers to change their time of consumption from peak to medium- and lower- price blocks. The most expensive units under these peak load blocks suffer a corresponding demand drop while the units at medium and lower peak hours increase their production levels to supply this shifted demand. As can be seen by the results presented in Table 7, the GEMED model is able to reproduce much more accurately these microeconomic production decision dynamics. The peak marginal units (CCGTs) reduce their production around 12% while the medium load level units (Coal) increase their production in 4.23% relative to the traditional CGE formulation.

This result is also very relevant for any environmental assessment because this can result in perverse outcomes under an unfavorable electricity technologies portfolio, as the one present at the Spanish case. The greenhouse gas emissions are slightly increased by the shift from cleaner CCGT to Coal power plants[13]. Even so, the global effect of the DR response policy studied in our case study is still very favorable under an environmental perspective due the higher magnitude of the conservation effect when compared to the indirect rebound and load shifting effects identified in this paper.

The results presented in this section show 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

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[13] This effect is highly dependable of the installed capacity structure of the country or region studied. In other electricity systems where more polluting power plants are concentrated in the peak periods the load shifting effects would actually act in the opposite direction, helping to reduce even more the emission levels.

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 in the evaluation of the policy.

Nevertheless, there is a clear tradeoff between the dimensions added by considering time differentiated electricity products and the computer requirements. This work intended also to alleviate the concern about the scalability of the GEMED model by presenting results for load block disaggregation levels of up to 200[14] for a medium-sized country like Spain.

4 Conclusions

This paper has presented for the first time a CGE model formulated with load-block disaggregation, location differentiation and technological detail in the electricity sector. 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 their availability, the electricity sector operation and future investments decisions, 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 for the evaluation of energy policies 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 when compared to BU and pure CGE models.

The GEMED model is able to estimate rebound effects, impossible to attain under a pure BU formulation. On the other hand, the electricity production decision is

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[14] Information about simulations carried out to prove the model scalability up to 540 load blocks and two different electricity markets can be requested from the authors. While the memory requirements of introducing more load blocks greatly increase, the marginal benefits of this tend to decrease after a certain number of load blocks.

much better represented than in a CGE model, as can be verified by the load shifting from peak units to base-load power plants, which cannot be observed under a non-BU paradigm. In our application this was reflected by a reduction of the use of gas powered power plants (CCGTs) and an increase of the demand for coal (which also presents a perverse side effect from the environmental point of view).

Therefore, the resulting GEMED model mimics the rich description of the electricity sector production decisions present in the BU electricity models while at the same time accounting for the indirect effects and inter-sectorial and institutional consequences of the energy policies assessed.

This work estimated a 6.5-11.2% potential rebound effect that could undermine the DR desired results. The recommended policy incentives necessary to increase DR could face important alterations under the presence of such a relevant indirect effect that would not be identified under an exclusive BU evaluation.

The results also showed that a traditional general equilibrium model could provide incorrect estimations on the electricity technologies use and fuel sectors variables in the order of 4.23% to -12.6% in both directions, even when compared to just a simple 6 load blocks GEMED alternative. The fuel substitution, quantities used, price levels, and emissions consequences could be mistakenly estimated under a CGE non-micro-founded and non-temporal-disaggregated scheme.

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 or intermittent sources, which are also becoming more and more relevant in electricity systems with the large-scale introduction of renewables.

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Appendix A – 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:
$\mathrm{Q}^{\mathrm{H}}_{\mathrm{ey,gne}}$	Household domestic non electricity goods demand
$Q^{H\_\mathrm{GEN}}_{\mathrm{ey},l,p,b}$	Household domestic electricity goods demand at location l - season p and load block b
$\mathrm{Q}^{\mathrm{TDeO}}_{ey}$	Household domestic electricity goods demand of transmission distribution and other electricity services
$\mathrm{P}_{\mathrm{ey,pf}}$	Price of production factor pf
Y^{H}_{ey}	Total household income
	Non electricity productive sectors:
$\mathrm{Q}^{\mathrm{pf\_SNE}}_{\mathrm{ey,pf,sne}}$	Quantity of production factor pf used in a specific sector sne
$\mathrm{Q}^{\mathrm{VA}}_{\mathrm{ey,sne}}$	Quantity of value added composite good produced by sector sne
$\mathrm{P}^{\mathrm{VA}}_{\mathrm{ey,sne}}$	Price of value added composite good of a specific sector sne

$Q^{II}_{ey,gne,sne}$	Quantity of intermediary input g used by a specific sector sne
$Q^{II\_GEN\_SNE}_{ey,l,dp,db,sne}$	Quantity of electricity good intermediary input at location l - season p and load block b used by a specific non electricity sector sne
$Q^{II\_TDeO\_SNE}_{ey,sne}$	Quantity of transmission, distribution and other electricity services intermediary input used by a specific non electricity sector sne
$Q^{S}_{ey,sne}$	Quantity of the commodity produced by a specific sector sne
$P^{S}_{ey,gne}$	Price of commodity produced by a specific sector sne (without foreign aggregations and production taxes)

Imports Armington Aggregation:

$Q^{M}_{ey,gne}$	Quantity of good gne imported from the exterior
$Q^{D}_{ey,gne}$	Quantity of aggregated imported and domestic produced supply of good gne
$P^{D}_{ey,gne}$	Price of Armington aggregated price of the good gne

Exports CET disaggregation:

$Q^{EX}_{ey,gne}$	Quantity of goods gne exported to the exterior
$Q^{Q}_{ey,gne}$	Quantity of final domestic market supply of good gne
$P^{Q}_{ey,gne}$	Price of final domestic good gne

Transmission, distribution and other electricity services:

$Q^{pf\_TDeO}_{ey,pf}$	Quantity of production factor pf used in the transmission, distribution and other electricity services
$Q^{VA\_TDeO}_{ey}$	Quantity of value added composite good produced by the transmission, distribution and other electricity services
$P^{VA\_TDeO}_{ey}$	Price of value added composite good of the transmission, distribution and other electricity services
$Q^{II\_GNE\_TDeO}_{ey,gne}$	Quantity of non-electricity intermediary input gne used by the transmission, distribution and other electricity services
$Q^{II\_GEN\_TDeO}_{ey,l,dp,db}$	Quantity of electricity good intermediary input at location l - season dp and load block db used by the transmission distribution and other electricity services
$Q^{II\_TDeO\_TDeO}_{ey}$	Quantity of transmission, distribution and other electricity services good intermediary input used by the electricity transmission, distribution and other electricity services
$Q^{S\_TDeO}_{ey}$	Quantity of the commodity produced by the transmission distribution and other electricity services
$P^{S\_TDeO}_{ey}$	Price of commodity produced by the transmission distribution and other electricity services (without foreign aggregations and production taxes)
$Q^{D\_TDeO}_{ey}$	Quantity of aggregated imported and domestic produced supply of transmission distribution and other electricity services
$P^{D\_TDeO}_{ey}$	Price of aggregated transmission distribution and other electricity services
$Q^{Q\_TDeO}_{ey}$	Quantity of final domestic market supply of transmission distribution and other electricity services
$P^{Q\_TDeO}_{ey}$	Price of final domestic transmission distribution and other electricity services

Electricity generation productive sector:

$Q^{pf\_GEN\_tech}_{ey,pf,l,p,b,t}$	Quantity of production factor pf used in the electricity sector at location l - season p and load block b by the production technology t

$Q^{VA\_GEN\_tech}_{ey,l,p,b,t}$	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
$P^{VA\_GEN\_tech}_{ey,l,p,b,t}$	Price of value added composite good of the electricity sector at location l - season p and load block b by the production technology t
$Q^{II\_GNE\_GEN\_tech}_{ey,gne,l,p,b,t}$	Quantity of non-electricity intermediary input gne used by the electricity sector at location l - season p and load block b by the production technology t
$Q^{II\_GEN\_GEN\_tech}_{ey,l,dp,db,gp,gb,t}$	Quantity of electricity good intermediary input at location l - season dp and load block db used by the electricity sector at season gp and load block gb by the production technology t
$Q^{II\_TDeO\_GEN\_tech}_{ey,l,p,b,t}$	Quantity of electricity transmission, distribution and other electricity services good intermediary input used by the electricity sector at season p and load block b by the production technology t
$Q^{S\_GEN\_tech}_{ey,l,p,b,t}$	Quantity of the commodity produced by the electricity sector at location l - season p and load block b by the production technology t
$P^{S\_GEN\_tech}_{ey,l,p,b,t}$	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)
$Q^{S\_GEN}_{ey,l,p,b}$	Quantity of the commodity produced by the electricity sector at location l - season p and load block b
$P^{S\_GEN}_{ey,l,p,b}$	Price of commodity produced by the electricity sector at location l - season p and load block b (without foreign aggregations and production taxes)
$Q^{D\_GEN}_{ey,l,p,b}$	Quantity of aggregated imported and domestic produced supply of electricity good at location l - season p and load block b
$P^{D\_GEN}_{ey,l,p,b}$	Price of aggregated electricity good at location l - season p and load block b
$Q^{Q\_GEN}_{ey,l,p,b}$	Quantity of final domestic market supply of electricity good at location l - season p and load block b
$P^{Q\_GEN}_{ey,l,p,b}$	Price of final domestic electricity good at location l - season p and load block b
	Imports:
$Q^{M\_GEN}_{ey,l,p,b}$	Quantity of good electricity imported from the exterior
$P^{M\_GEN}_{ey,l,p,b}$	Price of imported electricity
	Exports:
$Q^{EX\_GEN}_{ey,l,p,b}$	Quantity of good electricity imported from the exterior
$P^{EX\_GEN}_{ey,l,p,b}$	Price of imported electricity
	Government:
Y^{G}_{ey}	Total government income
E^{G}_{ey}	Total government expenditure
Y^{TAX}_{ey}	Total government taxes income
	Savings and Investments
S_{ey}	Total economy savings
S^{H}_{ey}	Households savings
S^{G}_{ey}	Government savings
S^{Ext}_{ey}	Foreign total savings

I_{ey}	Total investment
$\mathrm{Q}^{\mathrm{I}}_{\mathrm{ey,gne}}$	Quantity of non-electricity good gne demanded as investment good (electricity cannot be an investment good because it cannot be stored, at least in it commodity form)
	<u>Consumer Price Index:</u>
CPI	Consumer price index. Model numeraire.

Equations:

Household behavior:

$$Q^{H}_{ey,gne} = \frac{\bar{c}^{H}_{ey,gne}\left(1-\bar{s}^{H}_{ey}\right)Y^{H}_{ey}}{\left(1+\bar{tx}^{H}_{ey}\right)P^{Q}_{ey,gne}} \qquad ,\forall ey, gne$$

$$Q^{H\_GEN}_{ey,l,p,b} = \frac{\bar{c}^{H\_GEN}_{ey,l,p,b}\left(1-\bar{s}^{H}_{ey}\right)Y^{H}_{ey}}{\left(1+\bar{tx}^{H}_{ey}\right)P^{Q\_GEN}_{ey,l,p,b}} \qquad ,\forall ey, l, p, b$$

$$Q^{H\_TDeO}_{ey} = \frac{\bar{c}^{H\_TDeO}_{ey}\left(1-\bar{s}^{H}_{ey}\right)Y^{H}_{ey}}{\left(1+\bar{tx}^{H}_{ey}\right)P^{H\_TDeO}_{ey}} \qquad ,\forall ey$$

$$\begin{aligned} Y^{H}_{ey} &= \sum_{pf} P_{ey,pf}\bar{q}^{H}_{ey,pf} + \overline{transf}^{G-H}_{ey} \\ &+ \overline{psc}^{H}_{ey}\left(\sum_{sne} \bar{tx}^{SC\_SNE}_{ey,sne,pf=Labor} P_{ey,pf=Labor} Q^{pf\_SNE}_{ey,pf=Labor,sne}\right. \\ &+ \bar{tx}^{SC\_TDeO}_{ey,pf=Labor} P_{ey,pf=Labor} Q^{pf\_TDeO}_{ey,pf=Labor} \\ &+ \left.\sum_{l,p,b,t} \bar{tx}^{SC\_GEN}_{ey,l,p,b,t,pf=Labor} P_{ey,pf=Labor} Q^{pf\_GEN\_tech}_{ey,pf=Labor,l,p,b,t}\right) + \overline{transf}^{Ext-H}_{ey} \qquad ,\forall ey \end{aligned}$$

$$S^{H}_{ey} = \bar{s}^{H}_{ey}Y^{H}_{ey} \qquad ,\forall ey$$

Non electricity production sector:

$$\begin{aligned} &\left(Q^{pf\_SNE}_{ey,pf=Labor,sne}\right)^{\frac{1}{\bar{\sigma}^{VA}_{sne}}}\left(1-\bar{a}^{VA_L}_{sne}\right)\left(\left(1+\bar{tx}^{SC\_SNE}_{ey,sne,pf=Labor}\right)P_{ey,pf=labor}\right) \\ &= \left(Q^{pf\_SNE}_{ey,pf=Capital,sne}\right)^{\frac{1}{\bar{\sigma}^{VA}_{sne}}}\left(\bar{a}^{VA\_L}_{sne}\right)\left(P_{ey,pf=Capital}\right) \qquad ,\forall ey, sne \end{aligned}$$

$$CES\left(Q_{ey,pf,sne}\right) - Q^{VA}_{ey,sne} = 0 \quad \perp \quad p^{VA}_{ey,sne} \qquad ,\forall ey, sne$$

$$\begin{aligned} P^{VA}_{ey,sne}Q^{VA}_{ey,sne} &= \left(1+\bar{tx}^{SC\_SNE}_{ey,sne}\right)P_{ey,pf=Labor}Q^{pf\_SNE}_{ey,pf=Labor,sne} \\ &+ P_{ey,pf=Capital}Q^{pf\_SNE}_{ey,pf=Capital,sne} \qquad ,\forall ey, sne \end{aligned}$$

$$Q^{II}_{ey,gne,sne} = \bar{c}^{II}_{ey,gne,sne} Q^{S}_{ey,sne} \qquad ,\forall ey, gne, sne$$

$$Q^{II\_GEN\_SNE}_{ey,l,dp,db,sne} = \bar{c}^{II\_GEN\_sne}_{ey,l,dp,db,sne} Q^{S}_{ey,sne} \qquad ,\forall\ ey, l, dp, db, sne$$

$$Q^{II\_TDeO\_SNE}_{ey,sne} = \bar{c}^{II\_TDeO\_sne}_{ey,sne} Q^{S}_{ey,sne} \qquad ,\forall\ ey, sne$$

$$Q^{VA}_{ey,sne} = \bar{c}^{VA}_{ey,sne} Q^{S}_{ey,sne} \qquad ,\forall ey, sne$$

$$\begin{aligned} P^{S}_{ey,sne} Q^{S}_{ey,sne} + \overline{transf}^{G\_sne}_{ey,sne} - P^{VA}_{ey,sne} Q^{VA}_{ey,sne} - \sum_{gne} \left(1 + \bar{tx}^{Pdct}_{ey,sne}\right) P^{Q}_{ey,gne} Q^{II}_{ey,gne,sne} \\ - \left(1 + \bar{tx}^{Pdct}_{ey,sne}\right) P^{Q_{TDeO}}_{ey} Q^{II_{TDeO_{SNE}}}_{ey,sne} - \sum_{l,p,b} \left(1 + \bar{tx}^{Pdct}_{ey,sne}\right) P^{Q_{GEN}}_{ey,l,p,b} Q^{II_{GEN_{SNE}}}_{ey,l,p,b,sne} \\ - \overline{emiss\ rate}^{CO2}_{ey,sne} \bar{p}^{CO2}_{ey} Q^{S}_{ey,sne} \leq 0 \ \perp\ Q^{S}_{ey,sne} \geq 0 \ ,\forall ey, sne \end{aligned}$$

Imports Armington Aggregation:

$$\left(Q^{S}_{ey,gne}\right)^{\frac{1}{\bar{\sigma}^{VA}_{sne}}} \left(1 - \bar{a}^{D}_{gne}\right) \left(\left(1 + \bar{tx}^{Pdction}_{ey,sne}\right) P^{S}_{ey,gne}\right) = \left(Q^{M}_{ey,gne}\right)^{\frac{1}{\bar{\sigma}^{VA}_{sne}}} \left(\bar{a}^{D}_{gne}\right) \left(\bar{p}^{M}_{ey,gne}\right) \quad ,\forall ey, gne$$

$$Q^{D}_{ey,gne} - CES\left(Q^{S}_{ey,gne}, Q^{M}_{ey,gne}\right) = 0 \perp \lambda^{D}_{ey,gne} \qquad ,\forall ey, gne$$

$$P^{D}_{ey,gne} Q^{D}_{ey,gne} - \left(1 + \bar{tx}^{Pdction}_{ey,gne}\right) P^{S}_{ey,gne} Q^{S}_{ey,gne} - \bar{p}^{M}_{ey,gne} Q^{M}_{ey,gne} = 0 \qquad ,\forall ey, gne$$

Exports CET disaggregation:

$$\left(\bar{b}^{Q}_{gne}\right)^{\bar{\sigma}^{Q}_{gne}} \left(\left(1 + \bar{tx}^{Pdct}_{ey,Exp}\right) \bar{p}^{EX}_{ey,gne}\right)^{\bar{\sigma}^{Q}_{gne}} Q^{Q}_{ey,gne} = \left(1 - \bar{b}^{Q}_{gne}\right)^{\bar{\sigma}^{Q}_{gne}} \left(P^{Q}_{ey,gne}\right)^{\bar{\sigma}^{Q}_{gne}} Q^{EX}_{ey,gne} \quad ,\forall ey, gne$$

$$Q^{D}_{ey,gne} - CET\left(Q^{Q}_{ey,gne}, Q^{EX}_{ey,gne}\right) = 0 \ \perp\ \lambda^{Q}_{ey,gne} \ ,\forall ey, gne$$

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

Transmission, distribution and other electricity services:

$$Q^{pf\_TDeO}_{ey,pf} = \bar{c}^{pf\_TDeO}_{ey,pf} Q^{VA\_TDeO}_{ey} \qquad ,\forall ey, pf$$

$$P^{VA\_TDeO}_{ey} Q^{VA\_TDeO}_{ey} = \left(1 + \bar{tx}^{SC\_TDeO}_{ey}\right) P_{ey,pf\_Labor} Q^{pf\_TDeO}_{ey,pf=Labor} + P_{ey,pf=Capital} Q^{pf\_TDeO}_{ey,pf=Capital} \qquad ,\forall ey$$

$$Q^{II\_GNE\_TDeO}_{ey,gne} = \bar{c}^{II\_gne\_TDeO}_{ey,gne} Q^{S\_TDeO}_{ey} \qquad ,\forall ey, gne$$

$$Q^{II\_GEN\_TDeO}_{ey,l,dp,db} = \bar{c}^{II\_GEN\_TDeO}_{ey,l,dp,db} Q^{S\_TDeO}_{ey} \qquad ,\forall\ ey, l, dp, db$$

$$Q^{II\_TDeO\_TDeO}_{ey} = \bar{c}^{II\_TDeO\_TDeO}_{ey} Q^{S\_TDeO}_{ey} \qquad ,\forall ey$$

$$Q^{VA\_TDeO}_{ey} = \bar{c}^{VA\_TDeO}_{ey} Q^{S\_TDeO}_{ey} \qquad ,\forall ey$$

$$\begin{aligned} P_{ey}^{S\_TDeO} Q_{ey}^{S\_TDeO} + \overline{transf}_{ey}^{G-TDeO} - P_{ey}^{VA\_TDeO} Q_{ey}^{VA\_TDeO} - \sum_{gne} \left(1 + \bar{tx}_{ey}^{Pdct\_TDeO}\right) P_{ey,gne}^{Q} Q_{ey,gne}^{II\_GNE\_TDeO} \\ - \left(1 + \bar{tx}_{ey}^{Pdct\_TDeO}\right) P_{ey}^{Q\_TDeO} Q_{ey}^{II\_TDeO\_TDeO} \\ - \sum_{l,dp,db} \left(1 + \bar{tx}_{ey}^{Pdct\_TDeO}\right) P_{ey,l,dp,db}^{Q\_GEN} Q_{ey,l,gp,gb}^{II\_GEN\_TDeO} - \overline{em\imath ss\ rate}_{ey}^{CO2\_TDeO} \bar{p}_{ey}^{CO2} Q_{ey}^{S\_TDeO} \\ \leq 0 \ \perp \ Q_{ey}^{S\_TDeO} \geq 0 \qquad , \forall ey \end{aligned}$$

$$Q_{ey}^{D\_TDeO} = Q_{ey}^{S\_TDeO} \qquad , \forall ey$$

$$P_{ey}^{D\_TDeO} Q_{ey}^{D\_TDeO} = \left(1 + \bar{tx}_{ey}^{Pdction\_TDeO}\right)\left(P_{ey}^{S\_TDeO} Q_{ey}^{S\_TDeO}\right) \qquad , \forall ey$$

$$Q_{ey}^{Q\_TDeO} = Q_{ey}^{D\_TDeO} \qquad , \forall ey$$

$$P_{ey}^{Q\_TDeO} Q_{ey}^{Q\_TDeO} = P_{ey}^{D\_TDeO} Q_{ey}^{D\_TDeO} \qquad , \forall ey$$

Generation Electricity sector:

$$Q_{ey,pf,l,p,b,t}^{pf\_GEN\_tech} = \bar{c}_{pf,l,gp,gb,t}^{pf\_GEN\_tech} Q_{ey,l,p,b,t}^{VA\_GEN\_tech} \qquad , \forall ey, pf, l, gp, gb, t$$

$$P_{ey,l,p,b,t}^{VA\_GEN\_tech} Q_{ey,l,p,b,t}^{VA\_GEN\_tech} = \sum_{pf} \left(1 + \bar{tx}_{l,gp,gb,t_{if\ pf=labor}}^{SC\_GEN}\right) P_{ey,pf} Q_{ey,pf,l,p,b,t}^{pf\_GEN\_tech} \qquad , \forall ey, l, gp, gb, t$$

$$Q_{ey,gne,l,p,b,t}^{II\_GNE\_GEN\_tech} = \bar{c}_{gne,l,gp,gb,t}^{II\_gne\_GEN\_tech} Q_{ey,l,p,b,t}^{S\_GEN\_tech} \qquad , \forall ey, gne, l, gp, gb, t$$

$$Q_{ey,l,dp,db,gp,gb,t}^{II\_GEN\_GEN\_tech} = \bar{c}_{l,dp,db,gp,gb,t}^{II\_GEN\_GEN\_tech} Q_{ey,l,p,b,t}^{S\_GEN\_tech} \qquad , \forall\ ey, l, dp, db, gp, gb, t$$

$$Q_{ey,l,p,b,t}^{II\_TDeO\_GEN\_tech} = \bar{c}_{l,p,b,t}^{II\_TDeO\_GEN\_tech} Q_{ey,l,p,b,t}^{S\_GEN\_tech} \qquad , \forall\ ey, l, p, b, t$$

$$Q_{ey,l,p,b,t}^{VA\_GEN\_tech} = \bar{c}_{l,p,b,t}^{VA\_GEN\_tech} Q_{ey,l,p,b,t}^{S\_GEN\_tech} \qquad , \forall\ ey, l, p, b, t$$

$$\begin{aligned} P_{ey,l,p,b,t}^{S\_GEN\_tech} Q_{ey,l,p,b,t}^{S\_GEN\_tech} - P_{ey,l,gp,gb,t}^{VA\_GEN\_tech} Q_{ey,l,p,b,t}^{VA\_GEN\_tech} + \sum_{gne} \left(1 + \bar{tx}_{l,gp,gb,t}^{Pdct\_GEN}\right) P_{ey,gne}^{Q} Q_{ey,gne,l,gp,gb,t}^{II\_GNE\_GEN\_tech} \\ + \left(1 + \bar{tx}_{l,gp,gb,t}^{Pdct\_GEN}\right) P_{ey}^{Q\_TDeO} Q_{ey,l,p,b,t}^{II\_TDeO\_GEN\_tech} \\ + \sum_{dp,db} \left(1 + \bar{tx}_{l,gp,gb,t}^{Pdct\_GEN}\right) P_{ey,l,dp,db}^{Q\_GEN} Q_{ey,l,dp,db,gp,gb,t}^{II\_GEN\_GEN\_tech} \\ + \overline{em\imath ss\ rate}_{l,gp,gb,t}^{CO2} \bar{p}^{CO2} Q_{ey,l,gp,gb,t}^{S\_GEN\_tech} \leq 0 \ \perp \ Q_{ey,l,gp,gb,t}^{S\_GEN\_tech} \geq 0 \qquad , \forall\ ey, l, gp, gb \end{aligned}$$

$$Q_{ey,l,gp,gb,t}^{S\_GEN\_tech} = \bar{c}_{l,p,b,t}^{ii\_tech\_GEN} Q_{ey,l,gp,gb}^{S\_GEN} \qquad , \forall\ ey, l, gp, gb$$

$$P_{ey,l,gp,gb}^{S\_GEN} Q_{ey,l,gp,gb}^{S\_GEN} = \left(\sum_{t} P_{ey,l,gp,gb,t}^{S\_GEN\_tech} Q_{ey,l,gp,gb,t}^{S\_GEN\_tech}\right) - \sum_{t} \overline{em\imath ss\_allow}_{ey,t,l,gp,gb} \qquad , \forall\ ey, l, gp, gb$$

$$Q_{ey,l,gp,gb}^{D\_GEN} = Q_{ey,l,gp,gb}^{S\_GEN} + \bar{q}_{ey,l,gp,gb}^{M\_GEN} \qquad , \forall ey, l, gp, gb$$

$$P_{ey,l,gp,gb}^{D\_GEN} Q_{ey,l,gp,gb}^{D\_GEN} = \left(1 + \bar{tx}_{l,gp,gb}^{Pdction\_GEN}\right) P_{ey,l,gp,gb}^{S\_GEN} Q_{ey,l,gp,gb}^{S\_GEN} + \bar{p}_{ey,l,gp,gb}^{M\_elect} \bar{q}_{ey,l,gp,gb}^{M\_elect} \qquad , \forall ey, l, gp, gb$$

$$Q_{ey,l,gp,gb}^{Q\_GEN} = Q_{ey,l,gp,gb}^{D\_GEN} - \bar{q}_{ey,l,gp,gb}^{EX_{GEN}} \qquad ,\forall ey,l,gp,gb$$

$$\begin{aligned}
&P_{ey,l,gp,gb}^{Q\_GEN} Q_{ey,l,gp,gb}^{Q\_GEN} \\
&\quad = P_{ey,l,gp,gb}^{D\_GEN} Q_{ey,l,gp,gb}^{D\_GEN} - \bar{p}_{ey,l,gp,gb}^{EX\_GEN} \bar{q}_{ey,l,gp,gb}^{EX\_GEN} + \overline{mkt\_surplus}_{ey,l,gp,gb} \qquad ,\forall ey,l,gp,gb
\end{aligned}$$

Government:

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

$$\begin{aligned}
\mathrm{E}_{ey}^{G} = {} & \sum_{\mathrm{gne}} \left(1 + \overline{\mathrm{tx}}_{ey}^{G}\right) \mathrm{P}_{\mathrm{ey,gne}}^{\mathrm{Q}} \bar{\mathrm{q}}_{\mathrm{ey,gne}}^{\mathrm{G}} + \left(1 + \overline{\mathrm{tx}}_{ey}^{G}\right) \mathrm{P}_{ey}^{\mathrm{Q\_TDeO}} \bar{\mathrm{q}}_{ey}^{\mathrm{G\_TDeO}} + \sum_{\mathrm{l,p,b}} \left(1 + \overline{\mathrm{tx}}_{ey}^{G}\right) \mathrm{P}_{\mathrm{ey,l,p,b}}^{\mathrm{Q\_GEN}} \bar{\mathrm{q}}_{\mathrm{ey,l,p,b}}^{\mathrm{G\_GEN}} \\
& + \overline{\mathrm{transf}}_{ey}^{\mathrm{G-H}} \\
& + \overline{\mathrm{psc}}_{ey}^{H} \left(\sum_{\mathrm{sne}} \overline{\mathrm{tx}}_{\mathrm{ey,sne,pf=Labor}}^{\mathrm{SC\_SNE}} \mathrm{P}_{\mathrm{ey,pf=Labor}} \mathrm{Q}_{\mathrm{ey,pf=Labor,sne}}^{\mathrm{pf\_SNE}} \right. \\
& + \overline{\mathrm{tx}}_{\mathrm{ey,pf=Labor}}^{\mathrm{SC\_TDeO}} \mathrm{P}_{\mathrm{ey,pf=Labor}} \mathrm{Q}_{\mathrm{ey,pf=Labor}}^{\mathrm{pf\_TDeO}} \\
& \left. + \sum_{\mathrm{l,p,b,t}} \overline{\mathrm{tx}}_{\mathrm{ey,l,p,b,t,pf=Labor}}^{\mathrm{SC\_GEN}} \mathrm{P}_{\mathrm{ey,pf=Labor}} \mathrm{Q}_{\mathrm{ey,pf=Labor,l,p,b,t}}^{\mathrm{pf\_GEN\_tech}} \right) + \sum_{sne} \overline{transf}_{ey,sne}^{G\_sne} \\
& + \sum_{l,gp,gb} \overline{transf}_{ey,l,gp,gb}^{G\_GEN} + \sum_{t,l,gp,gb} \overline{emiss\_allow}_{ey,t,l,gp,gb} + \overline{\mathrm{transf}}_{ey}^{\mathrm{G\_TDeO}} \qquad ,\forall \mathrm{ey}
\end{aligned}$$

$$\mathrm{S}_{ey}^{G} = \mathrm{Y}_{ey}^{G} - \mathrm{E}_{ey}^{G} \qquad ,\forall \mathrm{ey}$$

$$\begin{aligned}
\mathrm{Y}_{ey}^{TAX} = {} & \sum_{\mathrm{sne}} \overline{\mathrm{tx}}_{\mathrm{ey,sne}}^{\mathrm{SC\_SNE}} \mathrm{P}_{\mathrm{ey,pf=Labor}} \mathrm{Q}_{\mathrm{ey,pf=Labor,sne}}^{\mathrm{pf\_SNE}} + \overline{\mathrm{tx}}^{\mathrm{SC\_TDeO}} \mathrm{P}_{\mathrm{ey,pf=Labor}} \mathrm{Q}_{\mathrm{ey,pf=Labor}}^{\mathrm{pf\_TDeO}} \\
& + \sum_{\mathrm{l,p,b,t}} \overline{\mathrm{tx}}_{\mathrm{l,p,b,t}}^{\mathrm{SC\_GEN}} \mathrm{P}_{\mathrm{ey,pf=Labor}} \mathrm{Q}_{\mathrm{ey,pf=Labor,l,p,b,t}}^{\mathrm{pf\_tech}} + \sum_{\mathrm{sne,gne}} \overline{\mathrm{tx}}_{\mathrm{sne}}^{\mathrm{Pdct}} \mathrm{P}_{\mathrm{ey,gne}}^{\mathrm{Q}} \mathrm{Q}_{\mathrm{ey,gne,sne}}^{\mathrm{II}} \\
& + \sum_{\mathrm{gne}} \overline{\mathrm{tx}}^{\mathrm{Pdct\_TDeO}} \mathrm{P}_{\mathrm{ey,gne}}^{\mathrm{Q}} \mathrm{Q}_{\mathrm{ey,gne}}^{\mathrm{II\_GNE\_TDeO}} + \sum_{\mathrm{sne}} \overline{\mathrm{tx}}_{\mathrm{sne}}^{\mathrm{Pdct}} \mathrm{P}_{ey}^{\mathrm{Q\_TDeO}} \mathrm{Q}_{\mathrm{ey,sne}}^{\mathrm{II\_TDeO\_SNE}} \\
& + \sum_{\mathrm{l,p,b,t,gne}} \overline{\mathrm{tx}}_{\mathrm{l,p,b,t}}^{\mathrm{Pdct\_GEN}} \mathrm{P}_{ey,gne}^{\mathrm{Q}} \mathrm{Q}_{\mathrm{ey,gne,l,p,b,t}}^{\mathrm{II\_GNE\_GEN\_tech}} + \sum_{\mathrm{sne}} \overline{\mathrm{tx}}_{\mathrm{sne}}^{\mathrm{Pdct}} \mathrm{P}_{ey}^{\mathrm{Q\_TDeO}} \mathrm{Q}_{\mathrm{ey,sne}}^{\mathrm{II\_TDeO\_SNE}} \\
& + \overline{\mathrm{tx}}^{\mathrm{Pdct\_TDeO}} \mathrm{P}_{ey}^{\mathrm{Q\_TDeO}} \mathrm{Q}_{ey}^{\mathrm{II\_TDeO\_TDeO}} + \sum_{\mathrm{l,p,b,t}} \overline{\mathrm{tx}}_{\mathrm{l,p,b,t}}^{\mathrm{Pdct\_GEN}} \mathrm{P}_{ey}^{\mathrm{Q\_TDeO}} \mathrm{Q}_{\mathrm{ey,l,p,b,t}}^{\mathrm{II\_TDeO\_GEN\_tech}} \\
& + \sum_{\mathrm{sne,l,p,b}} \overline{\mathrm{tx}}_{\mathrm{sne}}^{\mathrm{Pdct}} \mathrm{P}_{\mathrm{ey,l,p,b}}^{\mathrm{Q\_GEN}} \mathrm{Q}_{\mathrm{ey,l,p,b,sne}}^{\mathrm{II\_GEN\_SNE}} + \sum_{\mathrm{l,dp,db}} \overline{\mathrm{tx}}^{\mathrm{Pdct\_TDeO}} \mathrm{P}_{\mathrm{ey,l,dp,db}}^{\mathrm{Q\_GEN}} \mathrm{Q}_{\mathrm{ey,l,gp,gb}}^{\mathrm{II\_GEN\_TDeO}} \\
& + \sum_{\mathrm{l,gp,gb,t,dp,db}} \overline{\mathrm{tx}}_{\mathrm{l,gp,gb,t}}^{\mathrm{Pdct\_GEN}} \mathrm{P}_{\mathrm{ey,l,dp,db}}^{\mathrm{Q\_GEN}} \mathrm{Q}_{\mathrm{ey,l,dp,db,gp,gb,t}}^{\mathrm{II\_GEN\_GEN\_tech}} + \sum_{\mathrm{sne}} \overline{\mathrm{tx}}_{\mathrm{sne}}^{\mathrm{Pdction}} \mathrm{P}_{\mathrm{ey,sne}}^{\mathrm{S}} \mathrm{Q}_{\mathrm{ey,sne}}^{\mathrm{S}} \\
& + \overline{\mathrm{tx}}^{\mathrm{Pdction\_TDeO}} \mathrm{P}_{ey}^{\mathrm{S\_TDeO}} \mathrm{Q}_{ey}^{\mathrm{S\_TDeO}} + \sum_{\mathrm{l,p,b}} \overline{\mathrm{tx}}_{\mathrm{l,gp,gb}}^{\mathrm{Pdction\_GEN}} \mathrm{P}_{\mathrm{ey,l,gp,gb}}^{\mathrm{S\_GEN}} \mathrm{Q}_{\mathrm{ey,l,gp,gb}}^{\mathrm{S\_GEN}} \\
& + \sum_{\mathrm{gne}} \overline{\mathrm{tx}}_{\mathrm{Exp}}^{\mathrm{Pdct}} \bar{\mathrm{p}}_{\mathrm{ey,gne}}^{\mathrm{EX}} \mathrm{Q}_{\mathrm{ey,gne}}^{\mathrm{EX}} + \sum_{\mathrm{l,p,b}} \overline{\mathrm{tx}}_{\mathrm{Exp}}^{\mathrm{Pdct}} \bar{\mathrm{p}}_{\mathrm{ey,l,gp,gb}}^{\mathrm{EX\_GEN}} \bar{\mathrm{q}}_{\mathrm{ey,l,gp,gb}}^{\mathrm{EX\_GEN}} + \sum_{\mathrm{gne}} \overline{\mathrm{tx}}^{\mathrm{H}} \mathrm{P}_{\mathrm{ey,gne}}^{\mathrm{Q}} \mathrm{Q}_{\mathrm{ey,gne}}^{\mathrm{H}}
\end{aligned}$$

$$+\sum_{\mathrm{l,p,b}} \overline{\mathrm{tx}}^{\mathrm{H}} \mathrm{P}^{\mathrm{Q\_GEN}}_{\mathrm{ey,l,p,b}} \mathrm{Q}^{\mathrm{H\_GEN}}_{\mathrm{ey,l,p,b}} + \overline{\mathrm{tx}}^{\mathrm{H}} \mathrm{P}^{\mathrm{H\_TDeO}}_{ey} \mathrm{Q}^{\mathrm{H\_TDeO}}_{ey} + \sum_{\mathrm{gne}} \overline{\mathrm{tx}}^{\mathrm{G}} \mathrm{P}^{\mathrm{Q}}_{\mathrm{ey,gne}} \bar{\mathrm{q}}^{\mathrm{G}}_{\mathrm{ey,gne}}$$

$$+\overline{\mathrm{tx}}^{\mathrm{G}} \mathrm{P}^{\mathrm{Q\_TDeO}}_{ey} \bar{\mathrm{q}}^{\mathrm{G\_TDeO}}_{ey} + \sum_{\mathrm{l,p,b}} \overline{\mathrm{tx}}^{\mathrm{G}} \mathrm{P}^{\mathrm{Q\_GEN}}_{\mathrm{ey,l,p,b}} \bar{\mathrm{q}}^{\mathrm{G\_GEN}}_{\mathrm{ey,l,p,b}} + \sum_{\mathrm{gne}} \overline{\mathrm{tx}}^{\mathrm{Inv}} \mathrm{P}^{\mathrm{Q}}_{\mathrm{ey,gne}} \mathrm{Q}^{\mathrm{I}}_{\mathrm{ey,gne}}$$

$$+\sum_{\mathrm{sne}} \overline{emiss\ rate}^{CO2}_{sne} \bar{p}^{CO2}_{ey} Q^{S}_{ey,sne} + \overline{emiss\ rate}^{CO2\_TDeO} \bar{p}^{CO2}_{ey} Q^{S\_TDeO}_{ey}$$

$$+\sum_{\mathrm{l,p,b,t}} \overline{emiss\ rate}^{CO2}_{l,gp,gb,t} \bar{p}^{CO2}_{ey} Q^{S\_GEN\_tech}_{ey,l,gp,gb,t}$$

Savings and Investments:

$$\mathrm{S}_{ey} = \mathrm{S}^{H}_{ey} + \mathrm{S}^{G}_{ey} + \mathrm{S}^{Ext}_{ey} + \overline{\mathrm{transf}}^{\mathrm{Ext\_K}}_{ey} \quad , \forall \mathrm{ey}$$

$$\mathrm{S}^{Ext}_{ey} = \sum_{\mathrm{gne}} \bar{\mathrm{p}}^{\mathrm{M}}_{\mathrm{ey,gne}} \mathrm{Q}^{\mathrm{M}}_{\mathrm{ey,gne}} + \sum_{\mathrm{l,gp,gb}} \bar{\mathrm{p}}^{\mathrm{M\_elect}}_{\mathrm{ey,l,gp,gb}} \bar{\mathrm{q}}^{\mathrm{M\_elect}}_{\mathrm{ey,l,gp,gb}} - \sum_{\mathrm{gne}} \left(1 + \overline{\mathrm{tx}}^{\mathrm{Pdct}}_{\mathrm{ey,Exp}}\right) \bar{\mathrm{p}}^{\mathrm{EX}}_{\mathrm{ey,gne}} \mathrm{Q}^{\mathrm{EX}}_{\mathrm{ey,gne}}$$
$$- \sum_{\mathrm{l,gp,gb}} \left(1 + \overline{\mathrm{tx}}^{\mathrm{Pdct}}_{\mathrm{ey,Exp}}\right) \bar{\mathrm{p}}^{\mathrm{EX\_elect}}_{\mathrm{ey,l,gp,gb}} \bar{\mathrm{q}}^{\mathrm{EX\_elect}}_{\mathrm{ey,l,gp,gb}} - \overline{\mathrm{transf}}^{\mathrm{Ext-G}}_{ey} - \overline{\mathrm{transf}}^{\mathrm{Ext-H}}_{ey}$$
$$- \overline{\mathrm{transf}}^{\mathrm{Ext-K}}_{ey} \quad , \forall \mathrm{ey}$$

$$\mathrm{Q}^{\mathrm{I}}_{\mathrm{ey,gne}} = \frac{\bar{\theta}_{\mathrm{ey,gne}}}{(1+\overline{\mathrm{tx}}^{Inv}_{ey})\mathrm{P}^{\mathrm{Q}}_{\mathrm{ey,gne}}} \mathrm{I}_{ey} \quad , \forall \mathrm{ey, gne}$$

Market clearing conditions:

$$\sum_{\mathrm{sne}} \mathrm{Q}_{\mathrm{ey,pf,sne}} + \mathrm{Q}^{\mathrm{pf\_TDeO}}_{\mathrm{ey,pf}} + \sum_{\mathrm{l,gp,gb,t}} \mathrm{Q}^{\mathrm{pf\_tech}}_{\mathrm{ey,pf,l,gp,gb,t}} + \left(\sum_{\mathrm{l,gp,gb}} \frac{\overline{mkt\_surplus}_{ey,l,gp,gb}}{P_{ey,pf}} \right)_{if\ pf=Capital}$$
$$\leq \bar{\mathrm{q}}^{\mathrm{H}}_{\mathrm{ey,pf}} + \bar{\mathrm{q}}^{\mathrm{G}}_{\mathrm{ey,pf}} \perp \mathrm{P}_{\mathrm{ey,pf}} \quad , \forall \mathrm{ey, pf}$$

$$\mathrm{Q}^{\mathrm{H}}_{\mathrm{ey,gne}} + \bar{\mathrm{q}}^{\mathrm{G}}_{\mathrm{ey,gne}} + \sum_{\mathrm{sne}} \mathrm{Q}^{\mathrm{II}}_{\mathrm{ey,gne,sne}} + \mathrm{Q}^{\mathrm{II\_GNE\_TDeO}}_{\mathrm{ey,gne}} + \sum_{\mathrm{l,p,b,t}} \mathrm{Q}^{\mathrm{II\_GNE\_GEN\_tech}}_{\mathrm{ey,gne,l,p,b,t}} + \mathrm{Q}^{\mathrm{I}}_{\mathrm{ey,gne}} \leq \mathrm{Q}^{\mathrm{Q}}_{\mathrm{ey,gne}}$$
$$\perp \quad \mathrm{P}^{\mathrm{Q}}_{\mathrm{ey,gne}} \quad , \forall \mathrm{ey, gne}$$

$$\mathrm{Q}^{\mathrm{H\_GEN}}_{\mathrm{ey,l,p,b}} + \bar{\mathrm{q}}^{\mathrm{G\_elec}}_{\mathrm{ey,l,p,b}} + \sum_{\mathrm{sne}} \mathrm{Q}^{\mathrm{II\_GEN\_SNE}}_{\mathrm{ey,l,p,b,sne}} + \mathrm{Q}^{\mathrm{II\_GEN\_TDeO}}_{\mathrm{ey,l,p,b}} + \sum_{\mathrm{gp,gb,t}} \mathrm{Q}^{\mathrm{II\_GEN\_GEN\_tech}}_{\mathrm{ey,l,p,b,gp,gb,t}} \leq \mathrm{Q}^{\mathrm{Q_{GEN}}}_{\mathrm{ey,l,p,b}}$$
$$\perp \quad \mathrm{P}^{\mathrm{Q_{GEN}}}_{\mathrm{ey,l,p,b}} \quad , \forall \mathrm{ey, l, p, b}$$

$$\mathrm{Q}^{\mathrm{H\_TDeO}}_{ey} + \bar{\mathrm{q}}^{\mathrm{G\_TDeO}}_{ey} + \sum_{\mathrm{sne}} \mathrm{Q}^{\mathrm{II\_TDeO\_SNE}}_{\mathrm{ey,sne}} + \mathrm{Q}^{\mathrm{II\_TDeO\_TDeO}}_{ey} + \sum_{\mathrm{l,p,b,t}} \mathrm{Q}^{\mathrm{II\_TDeO\_GEN\_tech}}_{\mathrm{ey,l,p,b,t}} \leq \mathrm{Q}^{\mathrm{Q\_TDeO}}_{ey}$$
$$\perp \quad \mathrm{P}^{\mathrm{Q\_TDeO}}_{ey} \quad , \forall \mathrm{ey}$$

$$\mathrm{I}_{ey} = \mathrm{S}_{ey} \quad , \forall \mathrm{ey}$$

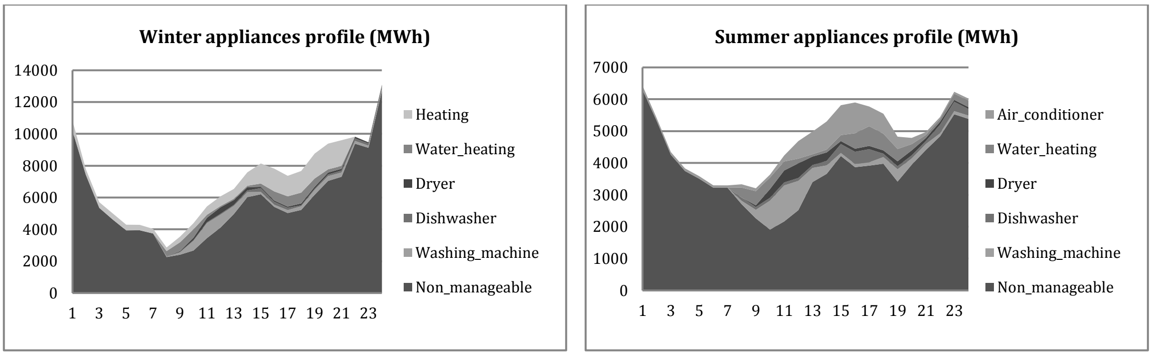
Consumer Price Index (model numeraire):

$$\mathrm{CPI} = \sum_{gne} \bar{\mu}^{Q}_{gne} \mathrm{P}^{\mathrm{Q}}_{\mathrm{ey,gne}} + \sum_{l,p,b} \bar{\mu}^{Q\_GEN}_{gne} \mathrm{P}^{Q\_GEN}_{\mathrm{ey,l,p,b}} + \bar{\mu}^{Q\_TDeO} \mathrm{P}^{\mathrm{Q\_TDeO}}_{ey} \quad , \forall \mathrm{ey, gne}$$

Appendix B – Demand Response Policy Assessment

The potential shifting and reducing loads from an increase on DR are estimated from the availability and technical characteristics of Spanish households' appliances. Figure 3 summarizes the average manageable load considered at each hour of the day, and Table 8 describes the load reduction potential from using more economic or efficient modes on the appliances evaluated. The equations used on the estimations of both bottom-up and top-down policy consequences are described below.

Figure 3. Manageable Appliance Load.



Source: own elaboration.

Table 8. 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
$\overline{gad\_price}_{y,l,p,b}$	Initial electricity base price
$\overline{\text{dur}}_{\text{l,p,b}}$	Load block duration (hours)
$\overline{\min\_sav}$	Minimum savings required to make the demand displacement

Variables:

$INCREASED\_DR\_LOAD$	Increased demand in load block due to demand response displacement (MW)
$DECREASED\_DR\_LOAD_{y,l,p,b}$	Decreased demand in load block due to demand response displacement (MW)

$CONSERVED\_DR\_LOAD_{y,l,p,b}$	Conserved demand in load block due to demand response displacement (MW)

Equations:

Active demand response demand balance:

$$\begin{aligned}\overline{\mathrm{demand}}_{\mathrm{y,l,p,b}} &+ INCREASED\_DR\_LOAD_{y,l,p,b} - DECREASED\_DR\_LOAD_{y,l,p,b}\\ &- CONSERVED\_DR\_LOAD_{y,l,p,b}\\ &\leq \sum_{\mathrm{t,f}} \mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}} + \overline{\mathrm{pimp}}_{\mathrm{y,l,p,b}} - \mathrm{PPUMPED}_{\mathrm{y,l,p,b}} - (\overline{\mathrm{own\_cons}}) \sum_{\mathrm{t,f}} \mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}}\\ &- \overline{\mathrm{loss}}_{\mathrm{y,l,p,b}} \left(\sum_{\mathrm{t,f}} \mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}} + \overline{\mathrm{pimp}}_{\mathrm{y,l,p,b}} + \overline{\mathrm{pexp}}_{\mathrm{y,l,p,b}} - \mathrm{PPUMPED}_{\mathrm{y,l,p,b}} \right)\end{aligned}$$

Maximum displacement:

$$DECREASED\_DR\_LOAD_{y,l,p,b} \leq \overline{\mathrm{displaceable\_load}}_{y,l,p,b}$$

Displacement balance:

$$\sum_{b} \left(INCREASED\_DR\_LOAD_{y,l,p,b} \overline{\mathrm{dur}}_{\mathrm{l,p,b}} \right) = \sum_{b} \left(DECREASED\_DR\_LOAD_{y,l,p,b} \overline{\mathrm{dur}}_{\mathrm{l,p,b}} \right)$$

Load conservation limit:

$$CONSERVED\_DR\_LOAD_{y,l,p,b} \leq \overline{\mathrm{conservable\_load}}_{y,l,p,b}$$

Minimum savings requirement:

$$\begin{aligned}\sum_{b} &\left(DECREASED\_DR\_LOAD_{y,l,p,b} \overline{gad\_price}_{y,l,p,b} \overline{dur}_{l,p,b} \right)\\ &- \sum_{b} \left(INCREASED\_DR\_LOAD_{y,l,p,b} \overline{gad\_price}_{y,l,p,b} \overline{dur}_{l,p,b} \right)\\ &\leq (1 - \overline{min\_sav}) \sum_{b} \left(\overline{displaceable\_load}_{y,l,p,b} \overline{gad\_price}_{y,l,p,b} \overline{dur}_{l,p,b} \right)\end{aligned}$$