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Hybrid Modeling for Electricity Policy Assessments

Tesis para la obtención del grado de doctor

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Abstract

Convergence between apparently disjoint assessment tools is a continuous desire in modeler's minds. This is no different when evaluating energy and environmental complex policies which entail multi sector effects not addressable without compromises between an exclusive Top-Down (TD) or Bottom-Up (BU) assessment.

This thesis aims to develop novel policy evaluation instruments suitable to assess the consequences of different electricity policies under both macro and micro economic perspectives simultaneously. The proposed approach should be able to account for the indirect effects characteristic of Computable General Equilibrium (CGE) models while also mimicking the detailed behavior of the electricity operation and investment present before only in bottom-up detailed models.

To fulfill this commitment, the thesis addresses three main challenges: the reconciliation between BU and TD data, the formulation of an electricity detailed CGE model (GEMED) and the formulation of a hybrid TD-BU model (H-GEMED).

The novelty of the GEMED model lies in two major aspects: the disaggregation of the electricity sector to include temporal, location and technology detail; and the introduction of the possibility for agents to react to time-varying prices under technological constraints.

H-GEMED goes one step further by formulating a complete integration between the TD and BU alternatives through a nonlinear mixed complementarity optimization model. BU features like the inclusion of backstop technologies and non-competitive technology retirement are taken care of endogenously under this approach with no problems.

Two relevant and current policy analysis cases are used to validate and compare the strengths and limitations of the instruments presented in the thesis. An electricity demand response program is used to assess the GEMED model and the macroeconomic consequences of a green tax reform and different tax revenue allocation schemes are evaluated using the H-GEMED model.

The results and conclusions obtained from the thesis strongly advocate in favor of the developed hybrid models whenever the assessment of the energy policy requires the rich description of the electricity sector production decisions and, at the same time, the accounting for indirect effects and inter-sectorial consequences.

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Acronyms

CGE	Computable General Equilibrium
DR	Demand Response
SAM	Social Accountability Matrix
TD	Top-Down
BU	Bottom-Up
CES	Constant Elasticity of Substitution
E3	Energy-Economy-Environment
GEMED	General Equilibrium Model with Electricity Detail
H-GEMED	Hybrid General Equilibrium Model with Electricity Detail
EU ETS	European Union Emission Trading System
GHG	Greenhouse Gas
TD&O	Transmission, Distribution and Other activities of the electricity sector
GEN	Electricity Generation Activity
MCP	Mixed Complementarity Problem
KKT	Karush-Kuhn-Tucker

1 Introduction[1]

The use of economic models for policy analysis has grown considerably in the past few decades. Increasing concerns about the scarcity of natural resources and environmental problems have led to the development of a discipline that it is now an important part of mainstream engineering and economics (Perman et al., 2012). Models began to redefine the role of energy as a relevant production input, alongside capital and labor (Ayres et al., 2013). In parallel, many pollutants have been incorporated as undesired output from production, such as acidifying substances and, more recently, greenhouse gases. The integration of these elements has led to the development of so-called Energy-Economy-Environmental or E3 models (Faucheux & Levarlet, 2002; Kemfert & Truong, 2009; Rodrigues et al., 2011). E3 models are useful tools for analyzing policies whose purpose is to shift economic activities onto a more sustainable path.

The 1973 energy crisis motivated the first energy-economic models, which focused on the macroeconomic consequences of energy shortages and the optimal allocation of energy resources (Manne et al., 1979; Nordhaus, 1980). The increasing demand for energy and the soaring prices of fossil fuels in 2007-08 led to a revival of the literature on the macroeconomic consequences of an increase in energy prices and on energy security issues (Markandya & Pemberton, 2010; Tang et al. , 2010).

Anthropogenic climate change and its links with energy consumption have also increased the interest in modeling the interactions between energy, economic variables and greenhouse gas emissions. Various types of models started to be developed in the 90s (see the surveys by Weyant, 1993, and Springer, 2003). Many models focus on the optimal emission abatement path, following a cost-benefit analysis, stemming from the pioneer DICE model by Nordhaus (1993). Integrated assessment models for climate change have also been developed which incorporate feedback effects from changes in natural systems into the economy (Alcamo, 1994; Manne et al., 1995). Finally, E3 models are also being applied to the power sector to provide insights of the trade-offs between competitiveness, security of supply and environmental effects when selecting appropriate technologies (Soloveitchik et al., 2002).

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[1] This section draws heavily from the book chapter written during the development of the thesis: Rodrigues, Gómez-Plana and Gonzalez-Eguino (2011).

E3 models are highly relevant in energy and climate policymaking. Governments are interested in future energy prices and demand, technology prospects and CO2 emissions when setting their main policies.

There are many different E3 models, but two main groups can be distinguished: 1) Bottom-Up (BU) or engineering models, which represent in detail the energy sector or a specific part of the economy; 2) Top-Down (TD) or economic models, which represent all sectors of the economy, and are usually general equilibrium models.

The choice of the framework to be adopted clearly depends on the issue in question. Regarding the BU alternative, no more than a partial equilibrium approach would be necessary if the interactions between the studied sector and the remaining economy were negligible. However, when feedbacks to other agents and indirect effects are considerable, TD models are more suitable for the job. But what happens when the problem to be addressed requires using simultaneously properties of both modeling approaches?

One can argue that choosing between exploiting the technological richness of BU or the indirect effects evaluation of TD models can represent a significant commitment when dealing with environmental issues. Undoubtedly, the detailed description provided by BU models of the set of technologies available is crucial in an analysis of environmental impacts, specifically in the case of energy sectors. At the same time, energy sectors can cause substantial indirect spillovers to other markets and, simultaneously, many climate issues can be presented as problems of a global nature, highlighting the importance of a comprehensive macroeconomic approach such as the one provided by TD models.

For example, an environmental policy such as the European Union Emission Trading System (EU ETS) could respond for approximately 60% of the greenhouse gas (GHG) emissions on Spain, but what about the perceived reaction of the diffuse sectors to these policies? Could it be the case that the assessed outcomes would be smoothed, changed or even reversed if the remaining sectors are considered?

The increase of consumers' price awareness promoted by an electricity demand response program for example could displace their electricity consumption profile reducing the peak prices and emissions in the generation sector. But what about its consequences if a rebound price effect and a consequent demand increase is considered? Would the demand increase induced by the lower peak prices be enough to significantly undermine the original policy assessment results?

The ambiguity in the modeling choice paradigm for E3 assessments emphasizes the failures of both independent BU and TD models to represent the linkages between the economic forces ultimately driving demand and production choices and their environmental consequences. This raises the necessity of pursuing alternative formulations capable of providing policy assessments for which individually neither TD nor BU grant a satisfactory analysis.

Whether by adapting the models employed or integrating their characteristics into a hybrid approach, much has been achieved in the relevant literature in successive attempts to reconcile BU energy operational detail and TD indirect effects evaluation.

However, before discussing the alternatives available we need to define which BU and TD modeling alternatives to focus on.

Accounting for up to one quarter of the total GHG emissions on Spain and presenting itself as one of the more dynamic sectors in the introduction of new environmental regulations and technological innovations, this thesis has chosen to focus on the electricity activity for representing the BU modeling paradigm. More specifically, a power generation operation and expansion model is used with this intent. Nevertheless, most of the conclusions and methodology presented in this work could be extended for different energy sectors and BU modeling alternatives.

In parallel, this thesis adopts a Computable General Equilibrium model (CGE) as the TD modeling representative, as it is one of, if not the most, used modeling approach on energy-economics assessments. The CGE model virtues in representing indirect substitution, income and rebound effects of economic systems are powerful capabilities for most of E3 policy assessments.

Now that we have limited our modeling scope, we can return to the main thesis subject: developing a novel policy evaluation instrument suitable to assess simultaneously both macro and micro economic perspectives of electricity policies evaluations.

Let us analyze first the relevant previous approaches.

1.1 The evolution of E3 CGE models

CGE models have been applied as a tool to assist economic decisions since the early 1970s. Evolving from Leontief's 1930s multi sector input-output models, one work is usually referenced as the seminal work in the CGE subject: Johansen's (1960) model of applied general equilibrium to analyze economic growth in Norway. Ever since, the CGE universe of applications expanded from fiscal issues to the evaluation of commercial and environmental policies, structural adjustments, income distribution, specific-sector production strategies, etc.

CGEs are macroeconomic models consistent with micro-foundations[2]. This means that "the demand and supply functions contained in the models are consistent with (in other words: can algebraically be derived from) the utility and profit maximization calculus which is at the core of the neoclassical economic theory of consumer and producer behavior" (Bernow et al., 1998, p.6).

The representation of economic decisions is based solely on a process of allocation of scarce resources. The market clearance conditions not only cause that the demand for factors in all the economy adapts itself to the endowment of factors available, but also promotes the complete utilization of any available resource. In other terms, the conservation of value determines that the production of goods provides the sufficient means for the producers (or for the owners of the means of production) to purchase what is produced, and hence, demand will behave as an adjustable variable, growing always when production grows. As consequence, under full employment and markets clearing the economic equilibrium will always be obtained within the efficient productive frontier.

The mechanism that makes possible to reach such equilibrium is the principle of substitution, presented in both the production and consumption sectors. This principle attests that under competitive assumptions the relative price from all the factors should be adjusted by the portfolio decisions of economic agents' choices until the equilibrium is reached.

The microeconomic foundations of CGE models undoubtedly provide consistence to the model formulation. They are mainly based on the works that followed Arrow-Debreu (1954) research about the existence and uniqueness of the equilibrium. Nevertheless, this benefit does not come without disadvantages. The functional forms applied, and between them the production function representation, usually place a high emphasis in the

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[2] Annex I describes step by step how to develop the CGE model used as the basis for the thesis developed model, altogether with the underlined assumptions inherent in the model equations.

mathematical requirements rather than on the microeconomic assumptions underlined on the model, potentially taking it apart from a real-world formulation.

Economic production functions are mathematical functions that describe the maximum physical output obtainable, at an existing technological level, from a combination of physical inputs. They result in a CGE equilibrium point that is always on the optimal product possibility frontier, through an allocation process of choice between the utilization of the most efficient production inputs.

However, the production function representation embodies a series of criticisms addressed by non-neoclassical economists. To classical and neoclassical economists, the fact that the production function only includes information about input substitution trade-offs on the efficient production possibility frontier is not a serious concern because of the assumption of agent rationality ('homo economicus'). However, heterodox economists underline the existence of a gap between the maximum efficient output and the actual produced output, which can be originated by diverse causes such as uncertainty, bounded rationality and asymmetric information. This gap would cause an interior solution to the production function problem that is usually unaddressed and unreachable in a traditional CGE formulation.

Even so, one of the most important economic criticisms to neoclassical production functions is derived from the Cambridge Capital Controversy Debate. Assigning production functions to individual firms' processes, despite being a simplification, is not a relevant concern when compared to the problem of how to determine aggregate production functions that reflect industry, sector or economy level behavior. The aggregation of the heterogeneous factors contained in production functions and the measurement of the factor input capital in physical terms are very problematic issues.

Non-neoclassical economists (Joan Robinson, Piero Sraffa, Luigi Pasinetti and Pierangelo Garegnani) argued that it is impossible to conceive an abstract quantity of capital that is independent of the rates of interest and wages. This creates endogenous theoretical problems to neoclassical models because this independence is a precondition for constructing an isoquant (or production function). Thus, the isoquant cannot be constructed and its slope measured unless the prices are known beforehand. However, inconsistently, the protagonists of aggregate production functions use the slope of the isoquant to determine relative factor prices. In order to solve this problem it would be necessary to construct a quantity-adjustable measurement of the physical capital.

Even assuming it is possible to create a meaningful measure of capital services, it is still necessary for the aggregation of firms' production possibility frontiers to maintain coherence with the production frontier for the economy as a whole. As Miller (2008) describes, the Leontief's theorem – which provides the necessary and sufficient conditions for the aggregation of any twice differentiable production functions – states that "aggregation is possible if and only if the marginal rate of technical substitution of the variables in the aggregate production function are independent of the variables that are not included." (Miller, 2008, p.12).

Thus, in a capital-labor input situation, the Leontief's theorem requires that labor has no effect on the substitution possibilities between the capital inputs; a condition clearly invalid in the real world where the choice of capital is influenced by the quantity and quality of labor available.

Neoclassical economists (such as Paul Samuelson, Robert Solow, Frank Hahn, Christopher Bliss, among others) argued that despite these theoretical shortcomings, aggregate production functions can still be defended on instrumentalist grounds if they provide a reasonably good description of the data. This affirmation was partially confirmed by specific empirical evaluations made by Fischer, Solow, Kearl and Shaikh (see Miller (2008, p. 14)).

In addition to the Cambridge Controversy criticisms, the neoclassical production function still presents an additional limitation to the applicability of CGE models. As Mitra-Kahn (2008) portrayed, the agents' functional forms predetermine the share with which each sector contributes to economic activity, providing an additional rigidity to the CGE model.

"More specifically the input shares of sectors will not change if the elasticities of substitution are all equal to one, and similarly the consumption shares will not change if demands are homothetic with unit price elasticities (again Cobb-Douglas). So a CGE model could not predict, nor deal with, any major structural changes like China's recent boom in manufacturing, or India's booming service outsourcing sectors. Simply because those productive parts of the economy are given a set percentage of the nations output in the benchmark, that will not change. To make adjustments to this, one would have to post facto change these shares exogenously, but it cannot be incorporated endogenously."

(Mitra-Kahn, 2008, pp. 60-61). Consequently, CGE models should focus on small changes of a known economy structure, and should not address issues related to structural changes of an entire economy.

Therefore, if the CGE policy analysis is limited to applications unrelated to substantial structural changes and excessive aggregation is avoided, and/or the empirical justification to the theoretical aggregation problems is accepted, then the neoclassical production functions become a possible valid simplification instrument to a CGE formulation.

Even so, the abstraction inherent in such economic production functions disregard aspects of physical production processes – including error, entropy or waste – and from the business processes – ignoring the role of management, of sunk cost investments and the relation of fixed overhead to variable costs.

Moreover, the statistic and econometric estimation of such production-describing equations move their defining parameters apart from real world technical parameters, hindering technology-changing assessments.

In order to overcome such criticisms, an important stream of publications aimed at embedding a special behavior to these singular and more complex agents and sectors inside the traditional CGE formulation. The so-called hybrid CGE modelling approach was born.

In a pure CGE model all sectors are represented as production functions with a substitution structure defined between all primary factors. Even so, it is possible to shape the representation of a specific sector utilizing more descriptive ways, for example by utilizing a BU partial equilibrium model instead of the economic production function to describe a sector production decision. The model that includes the CGE structure and in unison incorporates a detailed production description of a specific sector is then called a "hybrid model". This thesis' main subject is strongly related to this family of models.

The main objective of the hybrid approach is to better represent the sectors that contains more expertise, specificities and data available, and at the same time are more important to the policy to be evaluated. This allows a more refined model structure for these sectors production decisions, prices and quantities behavior. Additionally, the increased technological detail allows a wider range of possible policy evaluations, unattainable on the statically estimated production representation found on traditional CGE models.

Regarding the adoption of the BU alternative, as already mentioned, no more than a partial equilibrium approach would be necessary if the interactions between the studied sector and the remaining part of the economy were negligible. However, the majority of economic sectors entail indirect effects not addressed in the partial modelling alternative that could represent substantial challenges to certain policy assessments. This is even more meaningful when we consider policies directly related with a universal input like energy or, more specifically, electricity.

Undoubtedly, the energy sector is one of the most representative sectors for the utilization of the hybrid approach to evaluate policy issues (see IAEE special issue Yatchew (2006)). As Böhringer and Löschel described, "energy policies do not only cause direct adjustments on energy markets but produce indirect spillovers to other markets" (Böhringer & Loschel, 2006, p.136). This fact emphasizes the failure of bottom-up models to represent the linkage between energy demand and the economic forces ultimately driving the demand in an adequate manner, what points to probable benefits of the hybrid structure adoption[3].

1.2 State of the art of hybrid E3 models

There is a profusion of modelling alternatives in the literature applied to E3 policy assessments. Figure 1 tries to summarize these many alternatives in a schematic way.

The x-axis of Figure 1 represents the increase on macroeconomic detail in those models. This axis is usually associated with the TD modeling paradigm. Models within the econometric, economic growth and CGE tradition can be located along this axis.

Meanwhile, the graphic y-axis represents the engineering detail present on the models, mostly associated with the pure BU modelling paradigm. Least cost linear and non-linear programing models such as the Times model (Loulou et al., 2005) or the IIT GEPAC model (Ventosa, 2001) are typical examples of this modelling group.

The farther from the origin, the bigger is the presence of either engineering or economic detail in the model formulation. Models within the inner graphic area present some kind of mix between the properties of both TD and BU modeling alternatives. The closer to the

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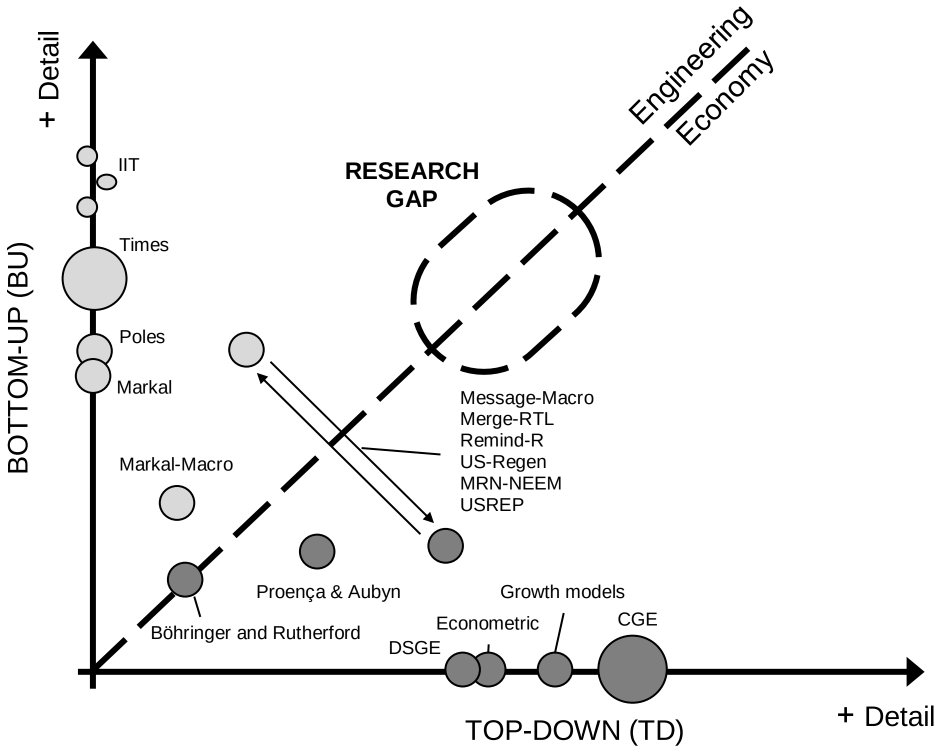
[3] As an illustration of some applications that benefits from the hybrid approach we have: the treatment of (energy) "tax interaction and tax recycling effects (e.g. Goulder 1995), terms-of-trade spillovers on international markets (e.g. Böhringer and Rutherford 2002), or induced technological change (e.g. Otto et al. 2006)" (Böhringer & Loschel, 2006, p.136).

45 degree line separating the engineering and economy formulations, the closer to a truly hybrid model you get.

Figure 1. Thesis research gap.



Source: own elaboration.

As can be seen, there are several alternatives that could represent a type of hybrid energy-economy model.

The simplest alternative is to introduce to either the BU or TD model information previously exclusive to the other modeling framework formulation. This alternative represents richer detailed models but that could be located still along one of the axis of the graphic represented in Figure 1.

Going one step further, one could develop a link between the two different model frameworks by sharing partial information between two models. This alternative (soft-link) is particularly popular among most of the more recent E3 publications. Message-Macro and Remind-R are examples of well-known assessment tools that use this principle.

Finally, the ultimate hybrid model would need to include properties from both modelling frameworks inside a single model (hard-link). Böhringer and Rutherford (2008) is the theoretical reference publication about the CGE and energy hybrid model formulation.

The hybridization process comprises clear advantages on reproducing better the real-world economy mechanics, however it is also associated with a theoretical-only solution or even intractability due to its complexity.

We intend to show in this thesis that it is perfectly possible to build a hybrid model that overcome most of the limitations of pure BU or TD models for electricity policy assessments. We begin by revisiting the hybrid modeling alternatives in more detail in the next section and underlining more precisely this thesis objectives.

1.1.1 Integrating a TD CGE and a BU electricity model

The first and more common alternative for providing the integration between the CGE coverage and the BU detail cannot be considered as a hybrid model in 'stricto sensu'. It consists of including a detailed energy representation into a TD model using the traditional economic formulation.

The pure TD alternative consists in formulating a top-down CGE model with detailed energy demand decisions represented directly by economic production functions with n-nested levels and specific technology substitution elasticities. The EPPA-MIT model (Paltsev, et al., 2005) and the work of González-Ruiz de Eguino (2007) are examples of the utilization of this approach. Both pure TD modeling with electricity production detail and a, yet to be seen, full BU-TD integration (the hybrid model) share the same departure point: the need for a compatible data framework scheme. The first of the main research gaps covered on this thesis emerges: overcoming the input incompatibilities between the macroeconomic annual accounts information and the microeconomic detailed technology and time-based description.

The **calibration process** proposed, responsible of reconciling the TD and BU data, should be capable of addressing simultaneously electricity **time, technology and location detail** at supply and demand levels, while respecting the macroeconomic balances. The following chapter (chapter 2) aims to answer this main question and present improvements to the methods used by the related literature.

Once a compatible and micro founded data framework is built, remains still the problem of making good use of it. A traditional CGE model is unable to simulate correctly policies that displace electricity supply and consumption on time, like for example the consequences of an increase in electricity demand response, the use of electricity car batteries for storage, the effects of changing to an electricity hourly tariff, and so on.

Therefore, this thesis second research gap can be identified: develop a **General Equilibrium Model with Electricity Detail (GEMED)**.

GEMED is an electricity extended CGE model that takes into consideration essential electricity supply and demand characteristics by introducing a reduced-form sector model that includes time, technology and location dimensions. Its formulation, application feasibility, virtues and limitations are presented on chapter 0.

This model clearly extends the current literature (McFarland & Reilly, 2004, Paltsev et al., 2005 and Sue Wing, 2008) that focuses on technological electricity generation detail only. The detailed electricity time and location components provide capabilities suitable for evaluating electricity policies that were once restricted to BU models, while retaining the inherent advantages of applying a widespread modeling formulation like the CGE modeling. However, the GEMED is still a pure TD model in essence. Extending the TD model is not the only alternative available, and certainly not the one that overcomes some crucial limitations of CGE models on electricity policy assessments, such as the mandatory respect of thermodynamic laws or deal with technologies retirement under a relative static statistically estimated production function framework.

To solve these issues one could make use of both TD and BU models together either by sharing part of their results (soft-link) or by integrating both models completely (hard-link).

A soft-linking approach employs sequential models to obtain a solution, i.e., soft-linking involves generating outputs from one model to serve as inputs to another model without physically connecting the two. As Mitra-Kahn (2008) points out, the “idea of having a ‘chain of models’ where a set of exogenous variables would be endogenous further down the chain was formulated in Robinson (1976) and described in Adelman and Robinson (1978)” (...) “and this idea has become very influential since.”

This approach can be unidirectional, i.e., use one model as parameter to define the other, or with feedback, where both models are solved until a convergence is reached. Wene (1996) for example analyses a soft-link approach to the BU engineering model MESSAGE and the TD macroeconomic model ETA-MACRO. Turton (2008) makes use of a soft-link approach with feedback between the ECLIPSE and MESSAGE-MACRO models, Böhringer and Rutherford (2006) present a similar iterative decomposition and

Labandeira et al. (2009) evaluate the effects on the Spanish economy of carbon policies based on the European Trading Scheme, applying a CGE model linked with a detailed BU electricity model.

Nevertheless, the soft-link approach is incapable of sharing all primal and dual information contained in the model solutions. Therefore, the best of both worlds – TD and BU virtues – could only be achieved through a hard-linking formulation, i.e. simultaneously solving both models as one.

The linkage adopted by Böhringer and Rutherford (2008) could be presented as the theoretical basis for a hard-link approach implementation, where the solutions to the models are obtained simultaneously through a mixed complementary problem (MCP). The Karush-Kuhn-Tucker (KKT) conditions of both CGE equilibrium model and BU engineering optimization problem are incorporated into a unique non-linear equilibrium problem.

However, the complex mathematical structure and the data compatibility issues limited the literature attempts to just building simplified versions or toy models of a hybrid model formulation, capable only of partially showing its potential, and lacking most of the crucial details necessary to correct apply these models to a thorough and real world policy evaluation. It remains to be seen an electricity hybrid formulation that includes the desired level of technology, time and location disaggregation for electricity policy assessments.

The third and the thesis most important research gap then arises: the creation of a hybrid model capable of mimicking the most important features of the TD and BU approaches for electricity policy assessments: the **Hybrid General Equilibrium Model with Electricity Detail (H-GEMED)**. H-GEMED is a mixed complementarity model that embodies simultaneously both CGE and a power generation operation and expansion model behavioral equations.

Chapter 4 presents our solution for this research question. It extends the unidirectional calibration process presented on Chapter 2 to deal with the more complex hybrid model requirements, and presents the formulation, application feasibility, strengths and limitations behind such modeling alternative. A relevant Spanish green tax policy reform assessment is used to illustrate all conclusions.

1.3 Thesis Objectives

As explained before, this thesis aims to develop novel policy evaluation instruments suitable to assess the consequences of different policies for the electricity sector on both macro and micro economic perspectives simultaneously. To fulfill this commitment, the proposed approach should be able to determine an equilibrium that would reflect the TD macroeconomic behavior of national economic agents and simultaneously respect the characteristics of a detailed BU microeconomic model of the electricity sector.

The TD chosen for representing the interactions of most economic agents is a Computable General Equilibrium model (CGE) [4]. This instrument was selected due to its adoption in numerous research studies in the literature, predominantly in E3 models, and due to its virtues for representing indirect substitution, income and rebound effects of economic systems.

In parallel, the thesis focus on evaluating specific electricity policies requires additional detail in the Bottom-up model responsible for representing the microeconomic behavior of the electricity sector. Therefore, a power generation expansion model following the structure of the former works of Ventosa (2001) and Linares et al. (2008) is adopted to represent the electricity sector behavior.

The first problem that arises is the reconciliation between BU and TD data. Different cost structures, diverse data sources (technical characteristics vs. company accounting) and data availability complicate this process.

Therefore, the thesis first research objective is to achieve a calibration procedure capable of introducing micro-founded BU technological and temporal data into the TD macroeconomic framework[5].

Once a compatible data framework is achieved, it is possible to define the General Equilibrium Model with Electricity Detail (GEMED). GEMED is an electricity micro-founded CGE model.

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[4] The CGE model developed for this thesis was published on Rodrigues, Linares and Gómez-Plana (2011).

[5] The calibration procedure developed for this thesis was published on Rodrigues and Linares (2014).

The novelty of the GEMED model lies in two major aspects: the disaggregation of the electricity sector to include temporal, location and technology detail; and the introduction of the possibility for agents to react to time-varying prices under technological constraints.

The GEMED model is capable of combining features from BU and TD models. It evaluates simultaneously optimal decisions for multiple productive and demanding sectors of the economy and it provides a detailed technological and time dependable behavior[6].

Nevertheless, the GEMED electricity sector production structure is still limited by the exclusive economic production function formulations. Retirement of non-competitive technologies and the inclusion of backstop technologies between other important effects are limited under this approach.

Therefore, the third and main objective of the thesis arises: The formulation of a completely integrated mixed complementarity hybrid TD-BU model, the H-GEMED model.

The thesis makes use of relevant and actual policy analysis cases to introduce the novel models developed and to verify their real-world applications. An electricity demand response program is evaluated with the GEMED model and the macroeconomic consequences of a Spanish green tax energy policy are evaluated using the H-GEMED model. Both case study analysis focus on demonstrating the models feasibility and evaluate their strengths and limitations when compared to the other alternatives available[7].

1.4 Outline and contents of the document

In order to address the previous objectives, this document is organized into five chapters. Besides this introductory chapter, the thesis comprises three self-contained chapters that, in principle, could be read independently (chapters 2, 3 and 4). Each one of these chapters includes specific conclusions as well as their own reference list.

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[6] The GEMED model developed for this thesis was published on Rodrigues and Linares (2014b).

[7] The policy assessment results presented on this thesis should be carefully considered for actual policy recommendations due to the partial outdate dataset used. Developing an up-to-date dataset for this thesis would comprise significant additional effort not essential to test the main thesis hypotheses. Further research is being under way using the same methodology to update the data and providing more suitable and actual policy recommendations.

Chapter 2 addresses the data compatibility between the engineering microeconomic and the economic macroeconomic data. A calibration procedure based on goal programing is proposed and its advantages compared to alternative literature approaches are underlined.

Chapter 3 formulates the GEMED model: a general equilibrium model with electricity temporal, technological and location disaggregation. A demand response policy assessment is carried out and the model results are compared to the alternative pure BU and TD formulations.

Chapter 4 presents the H-GEMED model: a hybrid BU and TD model that incorporates an electricity operation and expansion and a CGE model into a single mixed complementarity formulation. The H-GEMED model is applied to a green tax reform evaluation and the revenue allocation and their economic burden is analyzed.

Chapter 5 is the final chapter of the thesis dissertation, which summarizes the main conclusions drawn from the thesis developments together with the major original contributions. Additionally, potential lines for future research are identified.

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2 Data and Calibration[8]

2.1 Introduction

Computable General Equilibrium (CGE) models, even the more recent ones used for the analysis of energy and environmental policies (e.g. Rausch et al., 2011), do not typically include a detailed representation of the electricity sector. This may be explained in part by the rabbit-and-elephant analogy introduced by Hogan and Manne (1977) and reminded by Ghersi and Hourcade (2006): the role of the energy sector in the economy is small, and even smaller the one of the electricity part of it.

However, this analogy will probably not remain valid for a long time, at least for the contribution of electricity to the energy services: we are already experiencing an increased electrification of the energy services, and this will only grow in the medium term with the introduction of electric vehicles or other efficient appliances. Under this new scenario, representing correctly the electricity sector will be crucial for understanding the impacts of policies on technologies, fuels, and also on electricity prices, which in turn will influence other economic sectors.

This detailed representation needs the explicit consideration of the different technologies used to produce electricity (as already proposed by McFarland & Reilly, 2004, Paltsev et al., 2005 or Sue Wing, 2008). However, and more importantly, it also requires accounting for the fact that, since electricity is not currently easy to store[9], it cannot be handled as a single good, but as a time-differentiated one that requires different technologies and has different prices in different time periods.

Some CGE models have tried to account for this by including in their technology disaggregation different technology portfolios characterized by their capacity factor and time of use. McFarland and Herzog (2006) is one example that makes use of this information to divide base-load technologies (typically coal and nuclear power plants), intermediate load capacity (natural gas combined cycle plants) and peaking capacity (simple cycle gas turbines). However, they still include these different time-dependable electricity technologies under the same nested production function, i.e., they make use of

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[8] This section is based on Rodrigues and Linares (2014).

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

different production functions for the same technologies under peak and off-peak demand periods. This, although enriching the technology description, still implies the existence of a single electricity commodity, which presents average costs, prices and quantities. However, the information contained in average prices is not able to truthfully reflect the actual behavior of electricity prices in competitive, marginal-price electricity markets. For example, an increase in the electricity demand in hours of lower demand (off-peak periods) would present a cost lower than the average price of electricity, since the additional energy required could be produced in cheaper variable cost power plants. As a consequence, the increase in demand would actually decrease the average price of electricity, while increasing marginal prices in this off-peak period. Since marginal prices are the prices sent to the rest of the economy (not the average ones used by the typical CGE model) these will not able to represent correctly the impact of this demand increase on the rest of the economy.

Therefore, if we want to accurately represent the impact of energy or environmental policies on electricity prices, and of these prices on the rest of the economy, we need to consider an additional level of detail: time period detail, or, in power systems' jargon, load block detail. This is even more important for policies that change not necessarily the quantity but the moment of time in which electricity is consumed (such as those dealing with electric vehicles or demand response programs)[10].

In this chapter we present a methodology for introducing time period detail into a CGE model (together with technology and location[11] detail) which, as will be shown later, allows us to represent much better than in traditional CGE models the impact of energy policies on electricity prices and technologies, and in turn on the rest of the economy.

The key element of the methodology is the disaggregation of total electricity consumption into different "electricity commodities", which correspond to the different time periods considered, and which cannot be interchanged because of the impracticality of storing

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[10] Please note that load level detail does not mean disaggregating demand into sectoral loads, since that would not solve the problem of different marginal prices either, because of the physical configuration of the power system (which does not allow for differentiating sectoral loads).

[11] By location we refer to different, limited or non-connected power systems within the same economic region (and therefore linked through economic macromagnitudes). As mentioned earlier, it makes no sense to differentiate locations if connected to the same power system and there is no power congestions. For the sake of clarity, we will not refer much to location detail in what follows, given that the focus of the chapter is on the time-period detail.

electricity. This requires in turn a row and column disaggregation of the Social Accountability Matrix (SAM): additional rows for the different, time-dependent electricity commodities, and additional columns for each generation technology in each time period. This disaggregation requires a more complex, novel calibrating procedure, which is based on a bottom-up, power sector detailed model. The foundations are them created to develop the more powerful assessment tools that will be presented on the following thesis chapters.

Another contribution of this chapter is the proposal of an alternative calibration routine based on goal programming, which improves the accuracy and speed of the calibration process, and also allows us to create a perfectly micro-founded description of the electricity sector.

The chapter is structured as follows. Section 2.2 describes the methodology and the model used for introducing technology and load level detail into the CGE model. Sections 2.3 and 2.4 present the data requirements and results of the calibration methodology and compares them to previous approaches. Finally, we offer some conclusions and thoughts about further research on this area.

2.2 Methodology

Of course introducing time period detail into a CGE framework is not an easy task. This has led many researchers to adopt a partial top-down (TD) solution by making use of auxiliary bottom-up (BU) electricity models. Under this approach, the CGE model is fed exogenously by a bottom-up model that simulates the behavior of the electricity sector, as in Rutherford & Montgomery (1997) and Lanz & Rausch (2011)). However, the lack of detail in the electricity sector of the TD CGE model limits the information shared between these models to average values (with the disadvantages mentioned in the introduction).

Our approach is based instead on a pure CGE formulation that incorporates at the same time the technological and the time period detail at both the electricity demand and production levels. This requires adding a column and row disaggregation to the SAM matrix, while keeping the correspondence with the physical production characteristics of each production technology (thermodynamic efficiency, fuel use, self-consumption, availability, maintenance costs, specific subsidies, etc.), and also the compatibility with the market clearing and zero profit conditions embedded in the Social Accountability

Matrix (SAM) scheme. The data required for this disaggregation is acquired directly from a bottom-up model, and must be reconciled with the top-down data.

We achieve this by proposing a calibration procedure to reconcile BU and TD data, as in Sue Wing (2008), but extending it to include time period detail, besides also proposing a different calibration routine.

In a succinct manner, our methodology requires the following elements:

- Disaggregate the rows of the SAM to create different, time-dependent electricity commodities for each electricity-demanding sector.

- Disaggregate the columns of the SAM to differentiate between electricity generation technologies, as proposed already by Sue Wing (2008). However, since we are also considering different time periods, in which the electricity production function may be different, we also need to further disaggregate the technology columns into time periods to show the different contribution of each technology in each time period.

- Since the data required for the row and column disaggregation is not available at the macro level, feed the extended SAM with data from a bottom-up model with the appropriate detail for the electricity sector. The data required include generation and sectoral demand values, disaggregated by location, time period and technology, and marginal costs of electricity production and fuel costs along the same dimensions.

- Reconcile the original top-down data of the SAM with the additional bottom-up data using a goal programming algorithm that minimizes the deviations between them. Unfortunately, and compared to previous approaches, the fact that the time period disaggregation is required both for rows and columns[12] prevents us from solving the column and row disaggregation problems separately, so a joint calibration procedure is required.

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[12] Together with the existence of fixed costs and market surplus that need to be allocated within the time periods and therefore makes it necessary to consider simultaneously row (demand) and column (supply) variables.

Figure 1 shows a more detailed roadmap of our procedure. The different steps will be explained below.

1. Add to a SAM a column and row disaggregation to include technology, load block and location detail
2. Solve an electricity bottom-up model to obtain the optimal generation behavior for the electricity market.
3. Based on the solution of the BU model, determine the use of the technologies and also the different sources of variable and fixed costs.
4. Compare the difference between real world prices and the simulated electricity operation results at the benchmark year to determine the non-accounted costs and market imperfection rents not considered on the BU model.
5. Determine the distribution of fixed costs between load blocks by calculating the excedent of each load block after deducing the variable costs.
6. Obtain a non-balanced SAM by applying the previous results to the equations that translate the BU parameters into TD aggregates.
7. Insert the optimal operation production decision determined in step 1 and the income and costs distribution determined in steps 2-4 as parameters of the calibration model described in section 2.2.2, Annex II and Annex III.
8. The final result is a calibrated SAM that is microfounded by BU parameters and disaggregated in technology, location and time for the electricity generation activity.

Figure 2. The steps of our methodology

2.2.1 Disaggregating the SAM into additional columns and rows (step 1)

The disaggregation of the SAM into additional columns and rows is needed to provide (i) the characteristic electricity production technologies disaggregation, as in Sue Wing (2008), and (ii) the load level and the location zonal nodes detail in both the demand profile of economic agents and the available production portfolios of generation technologies. As mentioned earlier, time periods need to be differentiated both at the row and column level, whereas the technology disaggregation (time-differentiated) is done at the column level.

The desired electricity-detailed SAM must be able to reproduce the exact figures present at the original SAM, while also representing additional information about the different electricity activities - GEN (Generation) and TD&O (Transmission, Distribution and Other activities) - and their heterogeneity in time. A schematic representation of the extended SAM with this information can be found in Annex II[13].

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[13] The fully disaggregated SAM matrix is publicly available at the website: www.renatorodrigues.info

2.2.2 Using a bottom-up model to define the top-down detailed model (steps 2 to 5)

Using a BU operation model as a starting point instead of real-world data allows us to deal with a smaller set of data requirements necessary to achieve the convergence between the BU and TD methodologies. These models are widely available in the literature for different power systems. This work makes use of a bottom-up power generation expansion model, based on Linares et al. (2008)[14], to define not only the cost distribution between load blocks but also each technology production decision, variable and fixed costs amounts, and load block market imperfection rents.

The operation model aims to represent the competitive electricity market results by choosing the most inexpensive technologies to produce enough electricity to meet demand in the reference year. The model gives three key pieces of information: generation disaggregated by location, time period and technology; and marginal costs of electricity production and fuel use along the same dimensions.

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

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

After excluding the variable and fixed costs, the remaining resources represent all economic flows not explicitly described in our BU model. These flows are allocated to

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[14] This model is fully defined in Annex IV and the GAMS code is available at the website: www.renatorodrigues.info. The data required to feed the model is available on the same source and can be directly acquired from the power system ISO (independent system operator) and regulatory commission reports.

remunerate all market imperfections and the non-accounted costs, and they are treated as capital terms in the CGE model[15]. More details about how this allocation is done are given in the following section.

2.2.3 Accounting for variable and fixed costs in the SAM framework

Some costs are directly related to the amount produced (the very definition of variable costs). These costs are easily represented on a load block disaggregated scheme: Equations relating fuel, taxes, maintenance, and any other variable costs can be directly associated with the corresponding time disaggregated cell of the electricity extended SAM. Take for example the generation fuel costs. They are a function of the technology's thermodynamic efficiency (η), the fuel price ($\bar{p}^{fuel}$), the power generated by the technology at the each time period ($\overline{\mathrm{pgen}}$) and the duration of the load block ($\overline{\mathrm{dur}}$) (the detailed equations for all micro-macro expenditure relations are presented in Annex III).

$$\mathrm{VAR\_E\_II\_QE\_GEN} = \left(\sum_{\mathrm{fuel}} \eta\, \bar{p}^{fuel}\overline{\mathrm{pgen}}\right)\overline{\mathrm{dur}} \qquad 2.2\text{-}1$$

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

Other costs however can be problematic to represent in a time period disaggregated scheme: the most important is the amortization of fixed costs (including those resulting from excess capacity). Take for example the amortization of the power plants installed capacity. Fixed investment costs are usually paid under an annual amortization schedule. But the income used to pay such amortization in power

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

systems usually comes from marginal prices, as described by Pérez-Arriaga and Meseguer (1997).

In marginal-settling electricity markets, the market price should be equal to the marginal unit bid necessary for supplying the total demand. Therefore, for every non-marginal unit, peak demand periods contribute substantially more to the payment of fixed costs than off-peak periods. Moreover, each technology receives only the amount proportional to its use in the time period. In a perfectly competitive market and under an exhaustive representation of the activity costs, the sum of the total surplus obtained at each time period after deducting the variable costs should correspond exactly to the capital requirements for paying off the corresponding power plant capacity (and any other additional fixed costs). Any divergence from this outcome would result in an arbitrage opportunity in the market.

Unfortunately, real electricity markets are typically not perfectly competitive. And it is also very difficult to achieve an exhaustive representation of all costs. For example, complexity and dimensionality make it impossible to represent the costs associated with the unit commitment (weekly) problem, which includes ramping or start-up costs, in a yearly operation model like the one used here.

Therefore, the allocation of these costs requires a more complex procedure. First, we determine the BU model surplus for each time period by subtracting the variable costs from the total income for that period. The fixed costs are then allocated proportionally to the BU surplus in each time period.

Then, the calibration model determines the total generation surplus (market imperfection rents and BU model non-accounted costs) by subtracting the costs (fixed and variable) from the total income[16]. We do this by including equation 2.2-2 in the calibration model[17], in which the surplus for each time period becomes a variable of the model.

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[16] Income comes from the SAM's rows, while variable costs come from columns. Again, this is a reason for having to calibrate rows and columns together.

[17] The detailed equation for the generation balance and be found in Annex III, equation AIII-50.

Descriptive Version of Generation Balance Equation: 2.2-2

$$\begin{array}{c}Demand\\Receipts\end{array}\left\{\begin{array}{c}Households\ final\ electricity\ consumption\\+\ Sectors\ electricity\ consumption\ as\ intermediate\ input\\+\ TD\&O\ electricity\ consumption\ as\ intermediate\ input\\+\ Electricitiy\ sector\ electricity\ consumption\ as\ intermediate\ input\\+\ Government\ final\ electricity\ consumption\\+\ Electricity\ exports\ payments\end{array}\right.$$

$$=$$

$$\begin{array}{c}Electricity\\Production\\Expenditures\end{array}\left\{\begin{array}{c}Electricity\ generation\ intermediate\ input\ expenditure\ in\ non\ electric\ goods\\+\ Electricity\ generation\ intermediate\ input\ expenditure\ in\ electricity\\+\ Electricity\ generation\ production\ factors\ (labor\ and\ capital)\ payments\\+\ Electricity\ generation\ taxes\ payments\\+\ Net\ electricity\ CO2\ emissions\ payments\ (emissions-rights)\\+\ Electricity\ generation\ imports\ payments\end{array}\right.$$

$$+\ Total\ generation\ economic\ surplus$$

This representation is perfectly compatible with the direct consequences of a perfectly competitive market environment but can be also applied to our imperfectly competitive electricity market.

In case there are market imperfections, there will be a difference between the sum of variable and fixed costs (calibrated as mentioned before) and the real market-observed income for each time period. We can assume then that the difference between these two terms is the market imperfection rent. This information of market imperfection rents can be easily used to determine a mark-up price corresponding to each load block in a CGE model.

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

2.2.4 The reconciliation between BU and TD modeling: The calibration procedure (steps 6 to 8)

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

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

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

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

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

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

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

The explicit representation of the technological parameters allows for easily adding additional calibration restrictions that require keeping the merit order unchanged after the calibration process. Another alternative to improve the mathematical formulation is to use a goal programming approach. This option, adopted in this chapter and described in section 2.2.4.1, overcomes the problem of concentration of deviations, and additionally, has a completely linear formulation that can be presented as an advantage in comparison with the previously mentioned quadratic approach due to faster solving times and simpler assurance of global optimal solutions.

Finally, it should also be mentioned that the fact that time period detail must appear both at the row and column level makes it impossible to solve the disaggregation problem separately for rows and columns. Therefore, the calibration model needs to address both simultaneously, as described below.

2.2.4.1. The calibration model

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

Min:

$$\sum_{c} \mathrm{MAXIMUM\_DEVIATION}_{c} \qquad 2.2\text{-}3$$

Subject to:

<u>First Group: Chebyshev deviation equations:</u>

$$\mathrm{X_c} - \bar{\mathrm{q}}_c + \mathrm{N}_c - \mathrm{P}_c = 0 \qquad , \forall \mathrm{c} \qquad 2.2\text{-}4$$

$$\frac{\mathrm{N_c}}{\bar{\mathrm{k}}_\mathrm{c}} + \frac{\mathrm{P_c}}{\bar{\mathrm{k}}_\mathrm{c}} \leq \mathrm{MAXIMUM\_DEVIATION}_c \qquad , \forall \mathrm{c} \qquad 2.2\text{-}5$$

$$\mathrm{N_c}, \mathrm{P_c} \geq 0 \qquad , \forall \mathrm{c} \qquad 2.2\text{-}6$$

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

$$\overline{\mathrm{sam}}_{\mathrm{row1,column1}} =$$

$$\sum\nolimits_{(row_2,column_2)\in(row_1,column_1)} \mathrm{EXTENDED\_SAM}_{row_2,column_2} \qquad 2.2\text{-}7$$

$$\forall\ row_1, column_1$$

Third Group: Micro-founded macroeconomic aggregates:

$$\begin{aligned}&\mathrm{EXTENDED\_SAM}_{row_2,column_2}\\&= Variable\ Costs(\mathrm{X}_1,\dots,X_c) + Fixed\ Costs(\mathrm{X}_1,\dots,X_c) \qquad 2.2\text{-}8\\&+ Non\ accounted\ costs\ and\ market\ imperfections\end{aligned}$$

Where $\mathrm{X_c}$ are the technological parameter decision variables; $\overline{\mathrm{q_c}}$ are the desirable values of $\mathrm{X_c}$ (i.e. the benchmark technological parameter values); $\mathrm{N_c}$ are the negative deviation variables; $\mathrm{P_c}$ are the positive deviation variables; $\bar{\mathrm{k}}_\mathrm{c}$ are the deviation normalizations associated with the cth goal[18]; $\overline{\mathrm{sam}}_{\mathrm{row1,column1}}$ are the SAM benchmark data (Annex II, Figure 11); $\mathrm{EXTENDED\_SAM}_{\mathrm{row2,column2}}$ are the SAM macroeconomic aggregates of Figure 12 (Annex II) resulting from the calibrated variables; and $Variable\ Costs(\mathrm{X}_1,\dots,X_c)$ and $Fixed\ Costs(\mathrm{X}_1,\dots,X_c)$ are the functions that translate the BU technological parameters into macroeconomic aggregates.

The goal programming formulation adopted overcomes the concentration of deviations previously described in section 2.2.4 and, if added to the must-follow accountability constraints necessary to maintain the SAM equilibrium, determines the calibration procedure necessary to match the electricity BU and TD data, providing the basis to define the GEMED model to be presented on the following chapter.

Representing the macroeconomic aggregates in terms of the technological parameters offers a very important additional advantage to this calibration process. Additional constraints can be easily added to the calibration process to avoid any unrealistic, exaggerated or undesirable calibration results. With this intent, an additional merit order condition is added to the calibration model and its associated advantages are presented on the results section.

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[18] We consider the parameters normalized by their initial values, therefore $\bar{\mathrm{k}}_\mathrm{c} = \bar{\mathrm{q}}_c$.

In order to ensure the existence of a solution to the model proposed it is necessary that every cell of the new SAM is related to at least one of the calibrating parameters. Twelve technological and monetary parameters (x_i) were chosen to integrate the calibration process due to their importance for the electricity sector operation and investments decisions. They are listed in Table 1.

Table 1. BU electricity calibration variables.

Description	**Variable**
Thermodynamic efficiency (MWh/kg of fuel)	$\eta_{y,l,t}$
CO_2 equivalent content by fuel (tCO2e/MWh)	$\mathrm{CO2e\_CONTENT}_{y,t,f}$
Overnight new capacity investment costs (€/KW)	$\mathrm{OVERN\_COSTS}_{y,t}$
Operation and maintenance labor fixed costs (€/KW)	$\mathrm{OeM\_FOM}_{y,l,t}^{labor}$
Social contribution costs (€/KW)	$\mathrm{OeM\_FOM}_{y,l,t}^{sc}$
Operation and maintenance variable costs (€/MWh)	$\mathrm{OeM\_VOM}_{y,t}$
Fixed operation and maintenance equipment fixed costs (€/KW)	$\mathrm{OeM\_FOM}_{y,l,t}^{equip}$
Electricity production self-consumption (%)	$\mathrm{OWN\_CONS}$
Network losses (%)	$\mathrm{LOSS}_{y,l,p,b}$
Imports prices adjustments (%)	$P\_IMP\_ADJ_{y,l.dp,db}$
Exports prices adjustments (%)	$P\_EXP\_ADJ_{y,l.dp,db}$

Source: own elaboration.

The chosen calibration parameters are by no means the only selection possible to be made. However, each of the parameters chosen can be directly related with one of the main cost sources of the electricity sector activity represented in this thesis. Moreover, they are also the main parameters in the definition of the BU operation and expansion model used by this thesis.

2.3 Data requirements

One could argue that data requirements of a system that deals simultaneously with both bottom-up and top-down components would be overwhelming 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 in bottom-up or top-down models.

Starting from the top-down perspective, the data requirements are not larger than those found in any other CGE based policy assessment, such as the OECD-Green (Burniaux et al., 1992) or EPPA models (Paltsev, Reilly, & Jacoby, 2005). Most of the macroeconomic data is consolidated in a Social Accountability Matrix (SAM) for the reference year.

A SAM provides the underlying data framework for multisectoral and economywide models. It is a matrix representation of transactions in a socio-economic system. This framework articulates the generation of income by production activities and the distribution and redistribution of income among institutional groups (households, firms, government, foreign sector,…). A SAM includes both National Income and Product Accounts and the Input-Output Framework. In Spain, the Symmetric Input-Output Table is only published every several years, and the one used by this works dates 2005[19]. For a deep description of the building, accountancy rules and contents see, for example, Reinert and Roland-Holst (1997), Uriel et al. (1997), Round (2003) or European Commission (2003). The SAM used in this thesis was developed in Gómez-Plana (2014). 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.

The bottom-up data description requires a more extensive dataset. Firstly, for the demand side, we need to define the electricity demand of each agent at each specific time (to allow for the row disaggregation of the SAM). This work assumes different electricity consumption profiles for each different sector, institution and foreign agent in the economy. Electricity demand profiles for exports and imports 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, CNMC). Fuel producers (Coal, Oil/Nuclear[20] and Gas) and the manufacturing sector are assumed to be interruptible electricity demanders and, as assumed by the “Atlas de la Demanda Eléctrica Española” (REE, 1998) are considered to 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

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[19] The Spanish statistics institute published recently an update of their Input-Output table with a 2010 base year. However, the work comprised in updating the dataset used on this thesis was not justifiable because the previous dataset was perfectly suitable to test this thesis objectives hypotheses.

[20] The nuclear and oil sectors on this thesis are aggregated into a single sector due to the aggregation found on the data published by the Spanish statistics institute. This thesis did comprise the additional work of separating both sectors into their own individual accounts because the lack of relevance for the simulation objectives.

generation technologies consumption, the pumping generation 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. The resulting distribution of the disaggregation of sectoral electricity demand in time periods is summarized in Table 2 for the six load-block scenario considered as reference in the analysis.

Table 2. Distribution of electricity demand (in MWh) per sector and time period for the six load-block scenario.

		Holiday			**Workday**	
	Off-peak	**Medium**	**Peak**	**Off-peak**	**Medium**	**Peak**
Manufacturing	3,123,106	11,415,522	4,476,812	8,379,660	32,514,570	13,175,119
Coal	30,803	112,593	44,155	82,650	320,695	129,948
Oil-Nuclear	25,263	92,342	36,213	67,783	263,012	106,574
Gas	9,966	36,427	14,286	26,740	103,756	42,042
Electricity	2,573,622	7,268,800	2,315,528	6,045,305	16,376,310	5,872,247
Transport	258,345	944,299	370,325	693,170	2,689,625	1,089,854
Other Services	3,671,994	13,421,807	5,263,614	9,852,391	38,229,026	15,490,654
Households	2,255,999	8,898,662	4,162,636	4,094,640	19,704,071	8,023,716
Exports	678,367	1,961,752	467,308	1,273,922	3,905,006	1,274,460
Imports	486,599	1,485,329	551,844	1,057,800	3,120,102	1,385,878

Source: own elaboration based on REE, CNMC.

All the above-mentioned assumptions for demand profiles are not strong assumptions and are easily adaptable and reproducible for policy assessments in other regions and countries according their specific electricity consumption behavior.

Regarding the electricity supply side data, the database greatly increases with the modeler's desire of adding more detail to the sector. Nevertheless, the dataset used is very similar to well-developed bottom-up models such as MARKAL/TIMES (Fishbone and Abilock, 1981 and Loulou et al., 2005) and or MESSAGE (Messner and Strubegger, 2001, and Keppo & Strubegger, 2010).

The bottom-up information used in this work to describe the electricity production technologies[21] includes power plants construction time, life time, overnight costs,

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[21] 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).

O&M costs, availability factors, thermodynamic efficiency, fuel prices, pollutant emissions, emissions allowances and currently installed capacity, among others. They are presented in a summary fashion in Table 3 and Table 4. The complete list of parameters used on this work can be found on the Annexes included on this thesis.

Table 3. Relevant technology parameters.

	Constr time	Life time	Overnight Costs	Var. O&M	Fixed O&M	Peninsula Installed Capacity	Capacity factor
	Years	years	€2005/kW	€2005/ MWh	€2005 / kW	MW (2005)	%
Nuc	6	50	2680	0.5	89.5	7876	80%
NCoal	3	40	1265	1	25.2	9480	72.60%
ICoal	3	40	1265	1	25.2	1944	79.60%
CCGT	3	25	640	0.3	26	12224	89.40%
F-G	1	25	803	1.26	40.03	6647	76%
Hyd Res	4	50	1800	1.78	9.96	6087	100%
Hyd RoR	4	50	1800	1.78	9.96	7900	100%
Wind	1	20	1140	0	35	9800	NA*
ORSR	1	25	1202	2.4	48.08	2697	NA*
NRSR	1	25	340	2.7	10	6645	37%
Pump	4	50	1800	1.78	9.96	2670	100%

Source: own elaboration.

* Wind and ORSR follows statistically predefined production patterns.

Table 4. Relevant fuel related technology parameters

	Fuel	Conversion Efficiency	Fuel Heat Rate[22]	Fuel Price[23]	CO2	NOx	SOx	PM10
		KCAL / MWH			t/MWh	g/MWh	g/MWh	g/MWh
Nuc	Enriched Uranium	1972.8	337.46	672.93				
NCoal	Coal	2338.1	4.19	39.05	0.93	3088.6	7329	322.8
ICoal	Coal	2368.7	5.33	48.57	0.91	1500	5000	200
CCGT	Natural Gas	1770.0	10.00	5.78	0.40	1200	7	20
NRSR	Natural Gas	1732.2	9.60	5.78	0.41	1223.2	7.14	20.39
F-G	Fuel-oil	1908.3	9.62	50.62	0.77	916.7	2600	100
F-G	Natural Gas	4025.7	9.96	5.78	0.83	916.7	600	20

Source: own elaboration.

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[22] Enriched Uranium= GigaCAL/kg; Coal= GigaCAL/t; Natural Gas= GigaCAL/ thousands m3; Fuel-oil= GigaCAL/t.

[23] Enriched Uranium= €/kg; Coal= €/t; Natural Gas= €/ million Btu; Fuel-oil= €/barrel

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. Publicly available sources provided by governments, regulators and other agencies can be used for reproducing the methodology applied in this work for other countries.

Finally, and based on these inputs, Table 5 shows part of the results of the BU model that will be later fed into the calibration model. The table presents the electricity technologies production share in each load block considered, for three scenarios: one load block (which would correspond to the traditional CGE approach), six load blocks (used as a reasonable benchmark, and representing three daily load levels per day and two types of day), and 180 load blocks (information for this scenario is presented only in summarized form). It can be easily seen (by comparing the all blocks columns) how the contribution of the technologies changes when we increase detail in load blocks.

Table 5. Share of the power produced by each technology per load block, and marginal prices, resulting from the BU model.

	One l.b	**Six Load Blocks (in more detail)**							**180 l.b.**
	All blocks	**Holidays**			**Working Days**			**All blocks**	**All blocks**
		Off Peak	**Medium Peak**	**Peak**	**Off Peak**	**Medium Peak**	**Peak**		
Wind	8.8	12.98	9.99	8.55	10.85	8.19	6.94	8.79	8.79
Hyd Res	3.75	1.82	2.76	4.65	1.53	3.77	6.12	3.75	3.75
Hyd RoR	2.18	3.14	2.55	2.11	2.71	2.02	1.68	2.18	2.18
ORSR	2.86	3.15	2.77	2.64	2.73	2.9	2.95	2.86	2.86
Nuc	22.2	31.37	25.49	21.1	27.92	20.77	17.27	22.2	22.19
ICoal	5.45	7.7	6.26	5.18	6.86	5.1	4.24	5.45	5.45
NCoal	24.25	34.27	27.84	23.05	30.49	22.69	18.86	24.25	24.24
CCGT	30.51	5.57	22.34	32.72	16.91	34.56	29.94	28.4	27.32
NRSR	0	0	0	0	0	0	6.74	1.19	2.28
F-G (oil)	0	0	0	0	0	0	2.9	0.51	0.51
F-G (gas)	0	0	0	0	0	0	2.36	0.42	0.41
Pump	0	0	0	0	0	0	0	0	0.02
Average weighted price (€MWh)	53.64	53.64	53.64	53.64	53.64	53.64	112.76	64.06	65.34

Source: own elaboration. Share values in percentage.

As can be seen, the participation share of cheaper technologies are not much impacted by the amount of load blocks disaggregation. This happens because it is mostly their maximum production capacity and availability that restricts their use at all load block disaggregations. However, as we increase the load blocks number, we increase the representation of higher and lower load demand levels. The previously marginal production units could either lose part of its share because newly added lower load demanding blocks, or increase their production until their technical constraints binds at higher electricity demanding blocks. Meanwhile, steeper load levels could require even more expensive units to produce. This is clearly seen on the working day peak load block for the six load blocks case. As more blocks are considered, this effect becomes even more evident as we can attest by the necessity of pumping observed on the 180 load blocks case.

As we will see, considering higher load block disaggregation levels, and consequently representing more correctly the load demand spikes, can be very important when calibrating costs related with emissions for example, or even representing more accurately the different electricity price levels observed at different load blocks.

The BU model is used not only to provide the technologies production shares for the calibration model, but also to calculate the variable costs for each load block and the fixed costs for the reference year.

2.4 Results

In this section we present the results of our calibration exercise and compare it to those obtained with a traditional SAM calibration. In particular, we are interested in showing the influence of the level of detail in load-block disaggregation on the quality of the results, both in terms of the calibration itself, and also regarding the degree of technical realism of the results corresponding to the power sector representation. As will be seen, our results confirm the interest of introducing load-block detail in the CGE model.

Table 6 describes the simulation scenarios assumed in our research.

Table 6. Simulation scenarios.

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

Source: own elaboration.

Two different calibration strategies are used: the minimax one proposed in this chapter, and the quadratic form usually proposed in the literature. The quadratic method under the scenario LB_1 is used to compare our thesis formulation with another calibration method described in Sue Wing's work (2008). However, due to very dissimilar datasets (Spanish vs. United States data) and different use of parameters in the calibration process (technological parameters vs. aggregated shares) we can only say that the method presented in our thesis achieved a superior but similar level of magnitude in the calibrated parameters errors.

The results obtained by the SAM calibration model are presented in Table 7. Unfortunately, the disaggregated SAM cannot be presented in the chapter due to the difficulty of showing such a large matrix: even for the six load-block scenario, this means introducing 79 columns (12 technologies per load-block, plus TD&O) [24].

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[24] All data, results, models and additional software developed for this thesis are publicly available at the website: www.renatorodrigues.info.

Table 7. Parameter with maximum deviation after the calibration process.

	MiniMax (%)	**Quadratic (%)**	**Variable with max deviation**
LB_1	4.73%	8.59%	O&M equipment's fixed cost
LB_6	5.22%	9.48%	O&M equipment's fixed cost
LB_20	5.51%	10.00%	O&M equipment's fixed cost
LB_45	5.40%	9.80%	O&M equipment's fixed cost
LB_90	5.41%	9.81%	O&M equipment's fixed cost
LB_180	5.58%	10.12%	O&M equipment's fixed cost

Source: own elaboration.

The operation and maintenance equipment fixed costs ($\mathrm{OeM\_FOM}_{y,l,t}^{equip}$) faced by the electricity generation technologies was the parameter which required the larger adjustment from the original data, a 4.73% deviation under the LB_1 scenario when compared to the benchmark data. This is indeed an encouraging outcome if compared with the 10-20% range of most of the deviations estimated in the Sue Wing's work, especially when compared to the 43.2% maximum calibrated error (of steam turbine generation expenditures). Again, it is important to emphasize that this result does not prove that our calibration procedure is any better that Sue Wing's proposal, due to different datasets and different calibrated parameters.

Nonetheless, stronger conclusions can be drawn when comparing the quadratic formulation and the minimax alternative for the same dataset. Observing again Table 7 we can see that the minimax model consistently bests the quadratic alternative in terms of maximum errors in the calibrated parameters. Moreover, it requires less computer memory resources and achieves faster solving times.

We therefore argue that there are clear advantages in using the minimax calibration procedure described in this chapter. However, the largest advantage of the methodology proposed is in the use of a microeconomic-founded calibration of parameters as we will see next.

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

The second strong limitation is the fact that under the macroeconomic-based calibration, it is very difficult to include technology-based constraints in the calibration process to avoid unrealistic results. The importance of the micro-foundation is illustrated by the results presented in Table 8.

Table 8. Variable cost merit order of original and calibrated technology parameters without bottom-up cost order enforcing constraints.

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

Source: own elaboration. # = variable cost merit order.

Table 8 presents the variable cost merit order of the electricity production technologies under the original bottom-up parameters and under the calibrated parameters. As can be seen on the gray area, the calibration model changes the technologies merit order for all but one of the load blocks aggregations evaluated. In fact, the merit order changes concentrate at the most expensive peak technology units.

This is a strongly undesirable result of the calibration model. The emission levels, fuels used, technical restrictions, etc. of the peak units affected are very different. Any model built upon these calibrated data can present very strongly biased and incorrect results. This problem can be easily solved under a micro-founded calibration model as the one proposed on this chapter. The simple addition of a constraint enforcing merit order, impossible under a non-micro-founded approach, prevents initially cheaper technologies to become more expensive than their competitors. The results obtained in this work for the calibration model and the subsequent general equilibrium models (chapters 0 and 0) take into account such additional merit order constraint to provide more realistic policy assessments results.

2.5 Conclusions

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

This chapter has presented the first attempt to our knowledge at building temporal disaggregation into a SAM accountability scheme, while keeping technological detail. We have shown that this temporal disaggregation, up to a very significant number of load blocks, is feasible for a country like Spain, although our approach could of course be replicated for countries with similar national accounting and electricity sector data.

This contribution is coupled with some methodological improvements over existing technology-rich CGE models, in particular a minimax calibration procedure made possible by the micro-founded representation of the electricity macroeconomic accounts. Instead of the usual quadratic alternative, the minimax approach allows avoiding the concentration of deviations in some variables, which is a desirable property to avoid unwanted cost merit order changes in the electricity market settlement. Moreover, as our results show, the minimax model consistently bests the quadratic alternative in terms of the maximum deviations obtained for the calibrated parameters in our dataset.

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

The calibration procedure presented is the first necessary step to develop a CGE model capable of reproducing correctly the electricity price behavior in competitive wholesale markets. This attribute is particularly important in policy assessments that include load shifting, demand profile changes and technology substitution, as we will see on the following chapter.

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3 The GEMED Model[25]

3.1 Introduction

There is an increasing interest in the power sector about the role of demand in helping achieve a sustainable energy system (e.g. European Commission, 2011). Traditionally, demand (in particular households' demand) does not react to changes in prices or to changes in the power system conditions. However, in the future scenarios envisaged, demand would become active, responding to the signals sent by the system (prices or quantities) and thus helping it adapt to different situations such as the increased penetration of renewable energy (inherently variable in most cases) or network congestion problems. The increased participation of demand would also help these systems become more efficient, in economic, technical and environmental terms.

Indeed, these benefits are derived from the fact that this active role of demand would come from correcting a market failure: currently, most electricity markets feature a significant information asymmetry, 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[26].

Demand Response (DR) programs try to address this failure, by sending consumers hourly (or even more detailed) information about marginal costs or system constraints, and allowing them to change their consumption profile (and also their bills) accordingly. DR programs can be implemented in several ways, the most common being Real Time Pricing (RTP, consumers are exposed to real prices), Time of Use (TOU, time differentiated tariffs, defined in advance) or Critical Peak Pricing (CP, consumers are charged more when the system approaches its upper limit). Many of these programs are currently being implemented or considered in many regions of the US and Europe (e.g., Faruqui & Sergici, 2010). Consumers are responding to them basically shifting their demand from the time in which electricity

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[25] This section contents is based on Rodrigues and Linares (2014b).

[26] 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.

is more expensive to times in which it is cheaper. Given that sometimes consumption cannot be shifted (e.g., it may not make sense to shift air conditioning loads to the middle of the night), these programs usually result also in a reduction in overall electricity demand. These demand shifts and reductions produce in turn changes in the amount of electricity generated, in the type of technology and fuel used to do it, in the costs of the system, and also in its environmental performance. In principle, all of these changes would be beneficial, since we are correcting a market failure by providing more information.

However, for these programs to work, and for consumers to be interested in reacting to time varying prices, we need to be able to measure the changes in consumers' demand. This, which could not be done before, is now possible thanks to the advances in communication and metering technologies (such as smart meters). But this entails a significant cost. Therefore, the benefits coming from the correction of the market failure need to be compared against the cost of deploying the technology required.

Several attempts have been made at assessing the costs and benefits of these programs (see e.g. Conchado & Linares, 2012, for a review). However, the assessment of DR programs poses two important challenges, which have not been addressed together yet. First, we need to take into account the time at which electricity is produced and consumed, since that will also change how we use technologies and fuels. This can generally be achieved with detailed bottom-up (BU), engineering models for the electricity sector. But at the same time, DR programs will also modify electricity prices (differently in each time period), therefore changing electricity demand across the economy and also emissions and welfare. For assessing these changes computable general equilibrium (CGE) models are required. 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 programs like this one.

Therefore, we need to combine these features for the correct assessment of the costs and benefits of DR 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 and Aubyn, 2013), none of them have addressed the most critical issue, the temporal dimension. For policies such as DR programs (or the promotion of electric vehicles), the relevant factor is not the amount of electricity consumed or saved, but the moment at which this is done. In order to assess them correctly we need BU-CGE integrated models that include this temporal dimension. The previous chapter presented the first attempt to our knowledge at building temporal disaggregation into a CGE data framework, while keeping technological detail. In this companion chapter we apply this framework to build the GEMED model. A CGE model capable of more completely assesses the impacts of a residential DR program in Spain.

The model simulates endogenously the reaction of households to time-varying prices (as compared to flat prices in the benchmark). We allow households to shift some of their loads among time periods (typically moving them from peak to off-peak periods), and also to reduce some of them if they cannot be shifted. Then we look at the effects of these load shifts and reductions on electricity prices and demands, technology and fuel use, costs and welfare, and pollutant emissions. We also compare our results to the ones obtained either from a BU or a traditional CGE model. Our results show clearly the benefits of this new approach: the finer the time detail of the representation of the electricity sector, the more realistic is the assessment of the indirect and general equilibrium effects[27], and therefore, the better the evaluation of the policy effects.

Section 3.2 describes the improved CGE model, while section 3.3 describes the assessment and how the DR program is modeled. Section 3.4 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 3.5 presents some conclusions and research extensions.

3.2 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

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[27] In related literature these are known as the macroeconomic rebound effect (e.g. Herring & Sorrell, 2009).

uses the PATH solver to obtain a local optimal equilibrium point. The functional form and data requirements necessary to define the model are described shortly in this section. The description of the equations and a more exhaustive explanation of the model can be found in Annex V.

The model assumes two production factors, labor and capital, perfectly mobile across sectors and allocated according perfect competitive factors' market. 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 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)[28] and one energy intensive sector (Transport).

The assumptions made in the model and described here and in Annex V are very much in line with the usual ones in CGE literature and small countries closure assumptions (e.g. Shoven & Whalley, 1984; Devarajan, Lewis, & Robinson, 1986; Robinson, Yu, Lewis, & Devarajan, 1999; Paltsev et al., 2005 and Proença & Aubyn, 2013).

The novelty of the GEMED model lies in two major aspects: the disaggregation of the electricity sector to include temporal, location and technology detail; and the introduction of the possibility, for households, to react to time-varying prices under technological constraints. We describe them further in the following sections. For more detail about the disaggregation of the electricity sector see chapter 2.

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[28] As we will see, this 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 chapter. More policy-oriented researchs should consider a more exhaustive representation of production sectors according to the policy consequences to be evaluated.

3.2.1 Temporal disaggregation of the electricity sector

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 in this thesis we chose to adopt a relatively simple network component (TD&O) description[29]. The TD&O activity follows a traditional Leontief aggregation structure for combining the production factors and different intermediate inputs into a single TD&O service.

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[30]) and the 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 time periods, together with the impracticality of storing electricity. Meanwhile, the homogeneity within each time period 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 time period.

Figure 3 summarizes the representation of the electricity sector in the model.

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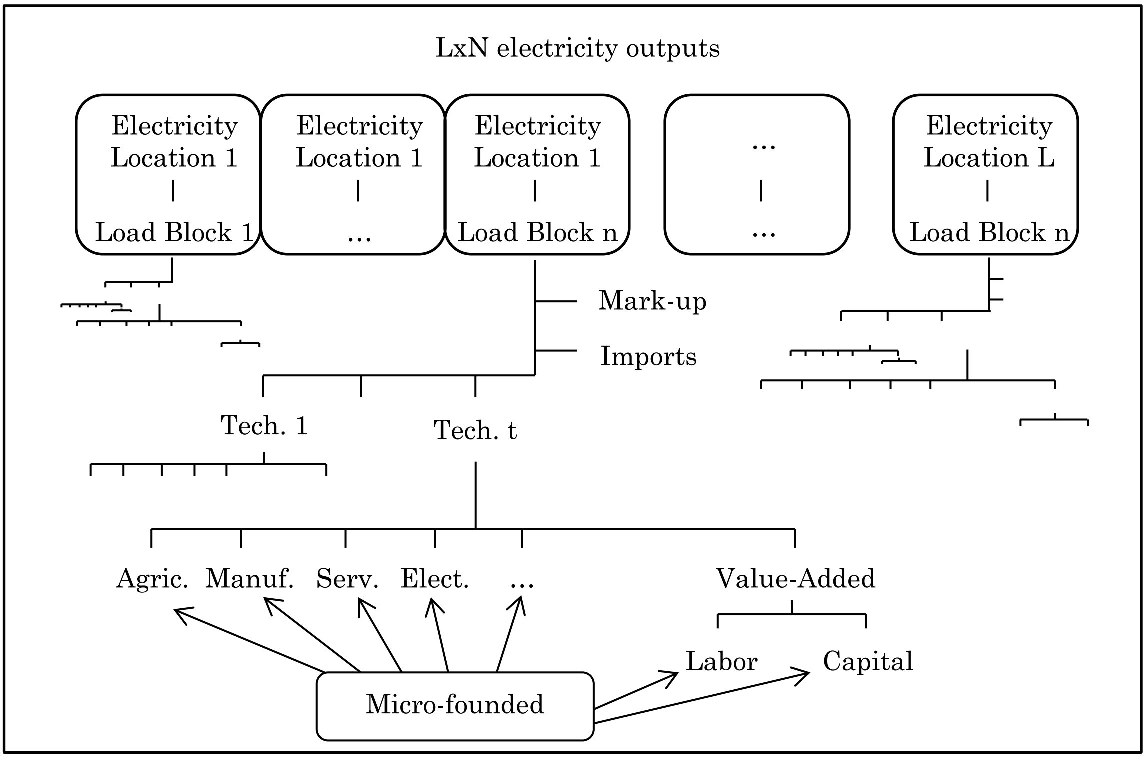
[29] A deeper policy assessment could make use of the same framework defined at this and the previous chapter in order to add electricity heterogeneity in time and location to the network component of the sector, however this work opted to take out such complications aiming for a clearer description.

[30] See note 11.

Figure 3. GEMED electricity sector structure.



Source: own elaboration.

From top to bottom, one can see that the electricity sector does not produce a single commodity but *l*x*n* differentiated products that represent the location (l) and time (n) heterogeneity. Each one of the different locations and time periods encompasses a different combination of import restrictions, technology availability and markup parameters aggregated through a Leontief production function to define the electricity production cost.

The limitations of existing network connections and historical electricity import profiles are used to exogenously determine the imported quantities at each time period. The markup component accounts for an extra monetary component in each production period that represents market imperfection rents, non-accounted costs and unevenly distributed fixed costs payments. The monetary flows obtained from the technologies' costs and import payments are then combined with the time period-dependable mark-up component to reflect the marginal price in electricity markets and any market imperfection or non-accounted costs of the bottom-up data calibration process.

The electricity produced by different technologies (or imported) is treated as a homogeneous product within a specific location and time period. However, each time period presents a pre-defined efficient combination of technologies that takes into account technical constraints to provide the electricity at the lower overall possible cost. The parameters that define the time period production functions are determined by the efficient production decision at each period given by the calibration process and the electricity operation and investment optimization model described in chapter 2, Annex IV and Annex V.

Going further down in Figure 3, each electricity generation technology[31] has its own production function to combine production factors (labor and capital) and intermediate inputs. Again, for the sake of simplicity a Leontief production function is used to define the aggregation of these inputs. However, the biggest difference here when compared to a traditional CGE is that these technological parameters are defined to be a direct result of technical bottom-up variable and fixed cost components[32]. As a result, the electricity generation technology costs in the CGE description are micro-founded by real world technological characteristics, which allow keeping the linkage between the generation technology costs (fuel, variable and fixed O&M, investment,…) and the associated microeconomic parameters (thermodynamic efficiency, wages, interest and discount rates, equipment and capital costs, etc.). This feature greatly increases the potential of the model for representing correctly technological evolution in the CGE assessment, as for example the inclusion of endogenous learning-by-doing processes.

Therefore, besides the explicit representation of different electricity production technologies, the detailed arrangement proposed by the GEMED model differentiates the electricity component according to the power system (*l* locations)[33]

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[31] 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).

[32] Annex III details the linkages between the macroeconomic aggregates and the microeconomic bottom-up parameters.

[33] Two independent markets defined by their geographical characteristics are considered in the Spanish case study presented in this thesis: the peninsular and the extra-peninsular geographical regions.

and, most particularly, by the time of consumption (*n* load blocks)[34]. The final GEN products are then represented by *n* times *l* dimensional vectors of prices and quantities, representing the production in different time periods (*n*) and the different power systems (*l*) within the economic region.

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 capable of representing the production technologies homogeneity within time periods, while at the same time addressing the time and location heterogeneity between different periods by the use of independent electricity products.

Finally, the complete CGE model is composed by $7+l\text{x}n$ goods and sectors: three for the fuel sectors, three for the typical electricity and energy demanders, one for the electricity TD&O and $l\text{x}n$ for the electricity GEN products (one electricity energy product for each load block *n* at each location *l* assumed).

3.2.2 Modeling a demand response program

As described briefly in the introduction, a DR program consists in sending time-varying prices to consumers (as compared to the usual flat prices). Consumers will then react to these prices by shifting loads to cheaper time-periods, or by reducing them if shifting makes no sense (e.g., shifting AC loads to the middle of the night is not very practical).

Our model takes advantage of the microeconomic-founded representation of the electricity sector, which makes it possible to develop a DR policy simulation based on households' micro data such as the available appliances and their load consumption characteristics. This level of detail allows us to directly obtain the simulation parameters based on real world information without any calibration previous step and, more importantly, to easily modify the policy scenario by adjusting the endogenous micro parameters present on the simulation. This way, the model allows us to follow a similar approach to bottom-up models like Conchado and Linares (2013), Andersen et al. (2006) and Brattle Group (2007).

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[34] 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 3.4.1, Table 10.

How do we then simulate the DR policy in the GEMED model? We basically introduce in the model another way to satisfy demand (other than generation), which is the shifting and conservation of the loads mentioned before. That is, we allow these loads to become variables of the model, we add some constraints to limit the extent to which this load reduction and shifting in time can be carried out, and we expose consumers to price profiles based on the marginal cost of the production of electricity. If marginal costs become too high, consumers will shift (or reduce) their loads to other time periods (subject to the constraints) so that marginal costs will become lower, and so that their total expenses in electricity are minimized (or their utility maximized).

The simulation and its equations are explained in more detail below.

As usual in CGE modeling, the households' consumption decision is modeled as one representative household, assumed to be welfare-maximizer through the choice of the optimal consumption bundle. The difference between the benchmark and the simulation is in the fact that households are allowed to change their electricity demand levels in different time periods by means of conservation measures or time shifting decisions, responding to changes in the electricity relative prices of time periods.

The household consumption decision can be expressed as the following optimization problem:

$$\underset{Q^H_g}{\text{Max:}} \quad \begin{aligned} U_{ey}\left(Q^H_1, \ldots, Q^H_g\right) &= \left(\sum_{gne} \bar{c}^H_{gne} \ln\left(Q^H_{gne}\right)\right) \\ &+ \sum_{l,p,b} \bar{c}^{H\_GEN}_{ey,l,p,b} \ln\left(Q^{H\_GEN}_{ey,l,p,b} + Q^{DR\_INCREASED\_LOAD}_{ey,l,p,b}\right. \\ &\left. - Q^{DR\_DECREASED\_LOAD}_{ey,l,p,b} - Q^{DR\_CONSERVED\_LOAD}_{ey,l,p,b}\right) \\ &+ \bar{c}^{H\_TDeO}_{ey} \ln\left(Q^{H\_TDeO}_{ey}\right) \end{aligned} \qquad 3.2\text{-}1$$

$$\text{Subject to:} \quad \sum_{gne} P_{gne} Q^H_{gne} + \sum_{l,p,b} P^{Q\_GEN}_{ey,l,p,b} Q^{H\_GEN}_{ey,l,p,b} + P^{H\_TDeO}_{ey} Q^{H\_TDeO}_{ey} \leq Y^{Available}_{ey} \qquad 3.2\text{-}2$$

As can be seen, welfare is represented by a Cobb-Douglas utility function, that combines the non-electricity goods (gne), the transmission services (TD&O) and the electricity consumption (GEN). The difference between the benchmark model (which does not allow for load shifting or reduction) and the simulation equations lies in the presence of the DR variables: $\mathrm{Q}_{\mathrm{ey,l,p,b}}^{\mathrm{DR\_INCREASED\_LOAD}}$, $\mathrm{Q}_{\mathrm{ey,l,p,b}}^{\mathrm{DR\_DECREASED\_LOAD}}$ and $\mathrm{Q}_{\mathrm{ey,l,p,b}}^{\mathrm{DR\_CONSERVED\_LOAD}}$.

$\mathrm{Q}_{\mathrm{ey,l,p,b}}^{\mathrm{DR\_INCREASED\_LOAD}}$ ($\mathrm{Q}_{\mathrm{ey,l,p,b}}^{\mathrm{DR\_DECREASED\_LOAD}}$) represent the load increase (decrease) in each time period as a result of a shift from (to) more expensive (cheaper) time periods. $\mathrm{Q}_{\mathrm{ey,l,p,b}}^{\mathrm{DR\_CONSERVED\_LOAD}}$ represents the load reduction due to demand conservation measures, such as using cold or Eco programs of appliances.

However, demand shifting or reduction is not unlimited, only some loads can be technically shifted in time or reduced. Therefore, the potential shifting and reduction of loads is limited by the availability and technical characteristics of the households' appliances. Therefore, there will be a maximum potential for load shifting and conservation, represented in the household maximization problem by constraints as the ones described below:

$$\mathrm{Q}_{\mathrm{ey,l,p,b}}^{\mathrm{DR\_DECREASED\_LOAD}} \leq \overline{\mathrm{displaceable\_load}}_{\mathrm{ey,l,p,b}} \qquad 3.2\text{-}3$$

$$\mathrm{Q}_{\mathrm{ey,l,p,b}}^{\mathrm{DR\_CONSERVED\_LOAD}} \leq \overline{\mathrm{conservable\_load}}_{\mathrm{ey,l,p,b}} \qquad 3.2\text{-}4$$

Load shifts are limited to the same period by assumption. This avoids unreal results as, for example, the possibility to move the use of a washing machine for an entire month. They are also assumed to be lossless and perfectly balanced, i.e., the total load decreased in a certain period must equal the total load increased in another (eq. 3.2-5).

$$\sum_{\mathrm{b}} \left(\mathrm{Q}_{\mathrm{ey,l,p,b}}^{\mathrm{DR\_INCREASED\_LOAD}} \overline{\mathrm{dur}}_{\mathrm{l,p,b}}\right) = \sum_{\mathrm{b}} \left(\mathrm{Q}_{\mathrm{ey,l,p,b}}^{\mathrm{DR\_DECREASED\_LOAD}} \overline{\mathrm{dur}}_{\mathrm{l,p,b}}\right) \qquad 3.2\text{-}5$$

Finally, in order to represent to a certain extent a non-infinite elasticity of the reaction of consumers to variable prices, 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 ($\overline{\mathrm{min\_sav}}$) of 5% in their electricity bills.

$$\begin{aligned}\sum_{b}\left(Q^{DR\_DECREASED\_LOAD}_{ey,l,p,b}P^{Q\_GEN}_{ey,l,p,b}\overline{dur}_{l,p,b}\right)&\\ -\sum_{b}\left(Q^{DR\_INCREASED\_LOAD}_{ey,l,p,b}P^{Q\_GEN}_{ey,l,p,b}\overline{dur}_{l,p,b}\right)&\\ \leq(1-\overline{min\_sav})\sum_{b}\left(\overline{displaceable\_load}_{ey,l,p,b}P^{Q\_GEN}_{ey,l,p,b}\overline{dur}_{l,p,b}\right)&\end{aligned}\tag{3.2-6}$$

The Karush-Kuhn-Tucker conditions obtained from the above described constraints are used to determine the MCP equation pairs that define the GEMED model with the policy simulation included.

3.3 An evaluation of a demand response program in Spain with the GEMED model

In this chapter we will assess the impacts of a hypothetical DR program to be carried out in Spain, using the GEMED model. This program consists in sending to all residential consumers in Spain (which represent 30% of the country's electricity demand) real time price signals, based on the wholesale electricity market. Consumers will then respond to these signals by shifting their loads in time or reducing overall consumption in order to minimize their electricity bill. We assume that the rest of the economy sectors (industrial, commercial, etc.) are not able to shift or reduce their loads.

The benchmark household load curves[35] (the distribution of electricity demand in time) and the starting time-varying electricity prices (to which households will respond in the DR program)[36] are shown in the following figure for the 6 and 180 load-block cases (Figure 4).

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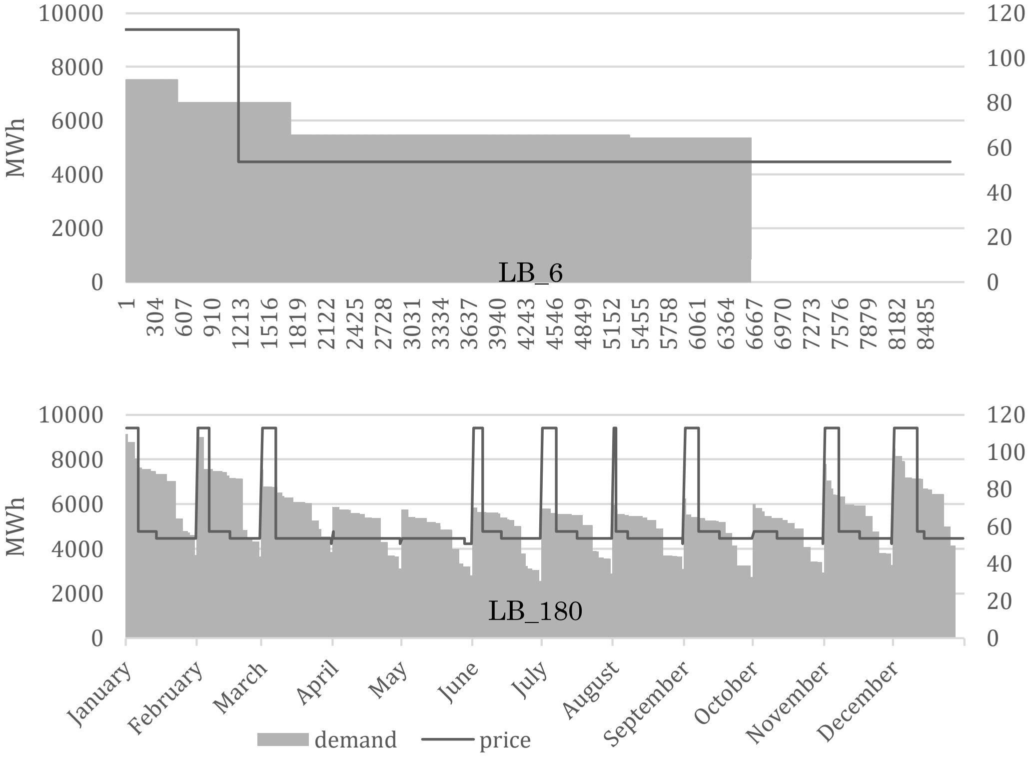
[35] The load curves used on the model are non-chronological within periods, and chronological between periods. The LB_6 scenario considers a single period (and therefore the load is distributed among the 8760 hours of the year), and the LB_180 scenario includes 12 monthly periods, within which 15 load blocks are defined.

[36] As described on section 3.2.2, electricity prices are calculated endogenously by the model following the electricity production characteristics and the endogenous household decision for engaging in DR measures. Under the benchmark, these prices reflect the business as usual electricity costs, assuming an inexistent household DR policy response.

Figure 4. Household benchmark load curve and electricity prices for 6 and 180 load blocks scenarios.



Source: own elaboration based on the benchmark simulation load block aggregations and prices.

The residential DR load shifting is restricted only to appliances that provide manageable services and that do not affect significantly the consumer habits. Following Conchado and Linares (2013) and Lu, Chassin, & Widergren (2004), we consider that the appliances with significant potential to be managed in the context of the DR program analyzed are: washing machine, dryer and dishwasher, electrical heating, air conditioning (AC) and water heating. Table 9 describes the load reduction potential (or conservation potential) from using more economic or efficient modes on the appliances considered.

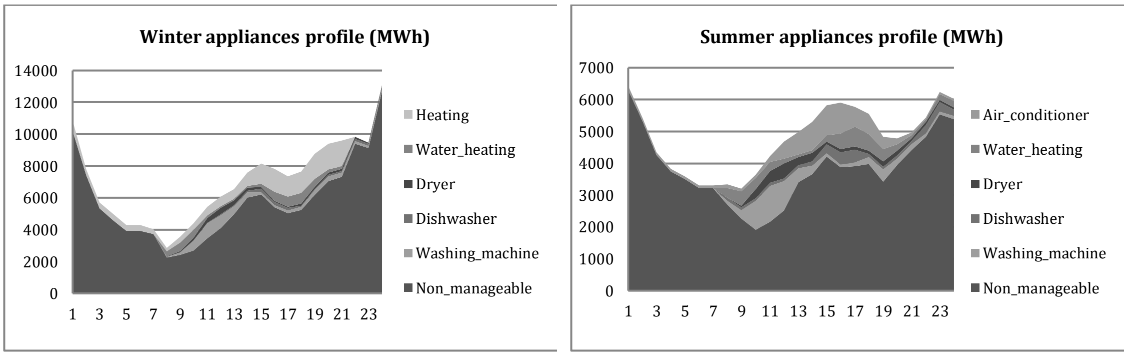
Table 9. Appliance conservation potential and displaceable loads.

	Appliances					
	Washing Machine	**Dishwasher**	**Dryer**	**Water Heating**	**Heating**	**Air Conditioner**
Conservation Potential	40%	40%	20%	30%	50%	50%
Displaceable Appliances	yes	yes	yes	no	no	no

Source: Conchado and Linares (2013).

The manageable loads do not constitute a significant share of the total electricity demand of households, with its share varying depending on the season and the time of the day. For illustrative purposes, Figure 5 shows the share of the average manageable load at each hour of the day calculated from the households' load and the assumptions described above.

Figure 5. Manageable Appliance Load.



Source: own elaboration based on households appliance load profiles from the CENIT-GAD project.

All data sources used are publicly available. Electricity demand profiles for exports and imports 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, CNMC). 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" (REE, 1998) are considered to 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 generation 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. The bottom-up information used in this work to describe the electricity production technologies[37] includes power plants construction time, life time, overnight costs, O&M costs, availability factors, thermodynamic efficiency, fuel prices, pollutant emissions, emissions allowances

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[37] See note 31.

and currently installed capacity, among others. These data were 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.

The simulation has been carried out using a Social Accounting Matrix (SAM) with 2005 as the base year[38]. Chapter 2 present in more detail the data necessary to define the CGE model and its calibration process.

The electricity load efficiency and shifting consequences of the DR policy are perfect to evaluate two of the most important electricity BU attributes added to the GEMED model: the time and the technological disaggregation. Besides, the GEMED model advantages when compared to the pure BU and pure CGE models can be easily identified from the policy results as we will see in the next section.

3.4 Results

3.4.1 Impacts of the DR program

In general terms, the global effect of the DR program in the economy is a reduction in demand, 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 time periods.

The more time periods 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 time periods provides more incentives to consumers to conserve and shift in time their electricity demand. Consequently, the more time periods considered, the larger are the load conservation, the income retraction, and the direct benefits in terms of cost savings of the DR program for the power system.

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[38] The data and results obtained on this chapter should be carefully considered for actual policy recommendations because the base year used for the macroeconomic data on the model is 2005. This does not mean any compromise for this chapter objective as it intends to compare the different models strengths and limitations when evaluating the same electricity policy assessment. Further research is being under way using the same methodology to update the data and providing a more suitable and actual policy recommendation.

We have run the model for different configurations in order to illustrate the influence of the number of time periods considered (see section 3.4.3). The following table (Table 10) describes the different configurations of the model.

Table 10. Time period configurations.

Scenario name	Number of time periods	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); 3 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.

In this section we will present only the results for LB_6, since it presents a good balance between level of time detail and manageability of the results. It should be remarked that the results presented in this section for all models aggregate the two different Spanish power systems (locations) considered in the original model for the sake of simplicity and brevity of explanations. We should also note 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.

It is also important to underline that the considered policy has very small consequences to the overall country economy due to its size. This is by no means a bad thing. CGE models are ideal to evaluate non-structurally changing policies and the validity of the conclusions do not change because of the policy size presented. Besides, all necessary precautions were made to avoid any computational approximation problem[39] when dealing with possible small variations, and a sensitivity analysis was carried out to attest the results stability under the same policy with a higher number of load block and DR penetration.

Table 11 presents results for electricity prices, demand, welfare and pollutant emissions. Table 12 in turn shows the distribution of demand and prices into time periods, all together with the observed changes to the different economy production sectors.

Table 11. Electricity generation sector results for the GEMED DR evaluation.

	Electricity Prices		**Electricity Demand**	**Emissions**	**Consumer savings**	**GDP**	**Households Wefare Changes[40]**
	before fixed costs[41]	**final**					
	%	**%**	**%**	**% CO2e** **% Acid e**	**106 €**	**%**	**%**
LB_6	-0.38%	0.20%	-1.07%	-0.98% -0.98%	138.07	-0.0331 %	0.0076%

Source: own elaboration. Percentage variations and consumer savings are accounted in relation to the benchmark values.

Carbon and acid emissions are reduced by the introduction of the DR program. However, this reduction comes basically from the overall demand reduction. As will be shown later, load shifting results in an increase in emissions (since natural gas is substituted by coal). However, the impact of load reductions is larger than the shifting impact on the overall of the economy.

Household welfare increases, as it would be expected from a policy that tries to correct an electricity market distortion by providing more information to the consumers. Nonetheless, the total economy effect also depends on the changes perceived by the productive sectors. As can be seen in the results, the electricity

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[39] Parameters and variables are normalized in the model to present similar range levels before the model is fed to the computational solver to avoid undesirable zero approximations for extremely small numbers.

[40] Household Welfare Change = - Equivalent Variation / Income.

[41] Electricity prices before annualized fixed cost amortization and additional estimated markup per load block.

demand contraction promoted by the conservation measures is more than enough to offset the consumer surplus increase, causing a larger drop in the surplus of the productive sectors, and consequently reducing GDP levels by 0.0331%. In fact, the policy, similarly to other energy-efficiency policies, creates a transfer of wealth from producers (who cannot adapt, in the short term, their generation portfolio to the change in demand) to consumers.

Table 12. GEMED LB_6 scenario results.

				Prices			**Quantities**		**Emissions**
				Bench	**DR**		**Bench**	**DR**	
					before fixed costs	**final**			
				p.u.	**p.u.** **%**	**p.u.** **%**	**p.u.**	**p.u.** **%**	**% CO2e** **% Acid e**
Products	**Electricity Generation**	**Holiday**	**Off-peak**	53.64	36.70 -0.19%	53.83 0.35%	11	11 -0.99%	-0.97% -0.97%
			Medium	53.64	37.06 -0.25%	53.86 0.40%	40	40 -1.21%	-1.19% -1.19%
			Peak	53.64	37.40 -0.30%	53.88 0.45%	17	16 -1.40%	-1.41% -1.41%
		Workday	**Off-peak**	53.64	37.05 0.13%	53.47 -0.32%	27	27 0.88%	0.87% 0.87%
			Medium	53.64	37.37 -0.23%	53.81 0.32%	108	107 -1.02%	-1.01% -1.01%
			Peak	112.76	80.97 -0.22%	113.46 0.62%	44	43 -2.12%	-2.13% -2.13%
		Weighted Total		64.14	44.85 -0.38%	64.27 0.20%	64.27 0.20%	244 -1.07%	-0.98% -0.98%
	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 %	-
	Capital			1		1.00 -0.0538%	374270	374270 0%	-

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

As regard to changes in the electricity technologies use and economy prices, Table 12 shows how the introduction of time detail for the electricity commodity allows representing them much more accurately.

Firstly, it is important to underline the differences between the two DR prices presented on both tables to represent the electricity sector results: the price before fixed costs and the final price. The first price represents a much better proxy of the marginal cost of producing electricity. It includes the technologies marginal production costs, imports, exports and production taxes applied to electricity. As it would be expected, the demand contraction caused by the DR efficiency and shifting effects allows the same demand to be provided by cheaper technologies available, dropping the electricity prices in most load blocks (from -0.19% to -0.30%).

The lower price levels are observed on all time periods except at the work-day off-peak load block. This specific hour block is clearly affected by the shifting effect of the policy: the demand on this block grows because the electric appliances shifting from more expensive hours. The prices effect is therefore reverted at this hour block (increasing 0.13%). The capability of representing this complexity within the electricity sector behavior is one of the attributes "borrowed" from the BU modelling paradigm that are now embedded on the GEMED model, differentiating it from traditional CGE models.

However, different from most BU evaluations, the GEMED model does not focus only on the variable costs effects of the DR policy. The fixed costs payments and an estimated markup term are also endogenous part of the model. These terms are included on the final price column represented on Table 11 and Table 12.

The fixed costs play an important role on the final price determination. While the policy promotes a drop in the total electricity demand, the annualized fixed costs payments remain constant. Therefore, the per MWh fixed costs payments increases. Assuming that the markup levels of the sector do not change, this per unit fixed costs increase is enough to offset the production cost gains in the simulated final price levels.

Even more important to the thesis objectives, it become evident the improvement of the policy mechanics representation under the GEMED model when compared to a traditional CGE model. The final prices of GEMED LB_6 scenario vary from 53.64

€/MWh to 112.76 €/MWh, 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 time period 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 time periods.

As previously mentioned, DR programs incentivize the consumers to shift their loads from peak to medium- and lower-price periods. The most expensive power plants supplying these peak time periods suffer a corresponding drop in demand while the power plants working in medium and off-peak hours (baseload plants) increase their production levels to supply this shifted demand. This result is also very relevant for any environmental assessment because this can bring perverse outcomes under an unfavorable electricity generation portfolio, as the one present in the Spanish case. Greenhouse gas emissions are slightly increased by the shift from cleaner CCGT to coal power plants[42]. Even so, the global effect of the DR 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 and load shifting effects identified.

As mentioned before, these results are of course different (and, in our opinion, better) than those obtained with pure BU or CGE models. Section 3.4.2 compares the results obtained with these models.

3.4.2 Comparison with a BU and a technology disaggregated CGE model

As mentioned in this chapter introduction, using a pure bottom-up (BU) model for the assessment of a DR program would represent well the changes in the electricity sector, but would not be able to measure the changes in electricity demand induced

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[42] 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.

in other sectors by the change in 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 policy for which a model such as GEMED is particularly well suited. To show this, we will now compare the results obtained with the six load-block GEMED model with those obtained with a pure BU model (the same one used to calibrate GEMED and described in Annex IV) and with a traditional CGE model, all of them using the same dataset[43].

Under a single time period 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 induced by DR programs (or, similarly, the introduction of electric cars, the consequences of smart metering or smart grid flexibility, time of use tariffs, 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 13.

Table 13. Comparison of results between the GEMED (with 6 load blocks) and a conventional CGE model (LB_1).

	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 €) (%)**
CGE (LB_1)	10164	10035 -1.26%	128 1.26%	128 1.26%	0 0.00%
GEMED (LB_6)	10292	10104 -1.82%	186 1.81%	169 1.64%	17 0.16%

Source: own elaboration.

In turn, the GEMED model is able to account for indirect effects not considered by BU models. Namely, the impact of lower electricity prices (induced by the DR program) on the electricity demand of other sectors, which results in a higher overall electricity demand. Similar effects could also happen for capital rents (as electricity

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[43] 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. Next chapter (Chapter 0) presents an alternative to overcoming such limitations, under the shape of a hybrid CGE-BU models.

is a highly intensive demander of capital), and to a lower degree for wages. The lower electricity prices induced by the DR program also reduce the attractiveness of the program itself, as it reduces the potential savings of adopting DR measures.

The effects described above act in the opposite direction of the reduction in the electricity demand promoted by the DR program, and therefore the results of the program will be dampened in a general equilibrium context compared to a BU model, which would overestimate them. As expected, the results of our 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 time period disaggregation alternatives assessed (see the quantity column on Table 14)[44].

Table 14. Electricity generation sector results for the GEMED model and the BU model demand response evaluations.

	Price		**Quantity**		**Emissions**		**Final consumer savings**	
	BU	**GE**[45]	**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

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 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 effects are considered in the LB_1 scenario. This corresponds to an 8.2%

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[44] 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 chapter focus on analyzing percentage changes between the benchmark and case study results.

[45] We only represent the GEMED electricity final prices in this table. The final prices include technology production costs, production taxes, imports and exports balance, fixed costs annualized payments and the estimated markup term for the sector.

general equilibrium effect[46] on quantities saved by the program when the indirect effects are taken into account.

GEMED prices vary much less (0.19% to 0.20%) and in the opposite direction[47] when compared to the partial equilibrium results (0.00% to -3.26%[48]).

The welfare change in a technology-only disaggregated general equilibrium model (-0.0022% on Table 15) is 3.45 times lower than the case that considers temporal disaggregation on the model (-0.0076%). This fact corroborates and extends the 2008 Sue Wing paper main conclusion: "The welfare costs of emission taxes in a hybrid model with a technologically rich description of the electric power sector generally exceed those in a top-down model in which the sector is represented by a smooth production function." (Sue Wing, page 3867, 2008). The experiment carried out in this chapter shows that this conclusion should not be restricted to either a carbon tax policy assessment or to the comparison between a traditional CGE and a technology disaggregated model. Table 15 shows that the welfare results when considering time disaggregation clearly exceed in magnitude those in a conventional CGE model. Therefore, not only technology disaggregation is crucial but also time disaggregation plays a meaningful role on the correct evaluation of an electricity policy.

Table 15. GEMED welfare change results.

	GDP %	**Households Welfare Change** %
LB_1	-0.0212%	-0.0022%
LB_6	-0.0331%	-0.0076%

Source: own elaboration.

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[46] As mentioned before, this can also be termed "macroeconomic rebound effect".

[47] As explained in the previous section, the opposite price direction is a consequence of the per unit fixed cost payment assumed in the model. Suboptimal and unnecessary excess capacity existent in the Spanish electricity sector and considered in the model could explain the importance of this term in the final price result of the sector.

[48] Bottom-up price variation for the 180 load blocks case.

If we examine more closely the variation of final quantities under the policy scenario we can identify even better the advantages of having a time disaggregation of the electricity commodity in the CGE model. The table below (Table 16) reproduces the variation in quantities of the previous tables, focusing on the differences between the time-period disaggregated scenarios.

Table 16. 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**	$\left(Q_{LB\_6} - Q_{LB\_1}\right)\frac{GDP\ Electricity}{GDP\ Economy}$
		% 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%

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 16) that some sectors present much larger differences when we compare the results from the single (LB_1) and the six (LB_6) time period 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 previous 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 become more evident.

3.4.3 Sensitivity to the number of time periods modeled

Finally, we also show the sensitivity of our results to the number of time periods considered in the GEMED model (as shown in Table 10).

Table 17 shows the results for prices, quantities, emissions and final consumer savings for different time period configurations.

Table 17. Electricity generation sector results for the GEMED model under different time period configurations.

	Price	**Quantity**	**Emissions**	**Final consumers savings**	**GDP**	**Households Welfare Change**
	%	%	% CO2e % Acid e	**10^6 €**	%	%
LB_1	0.19%	-1.01%	-1.01% -1.01%	109.59	-0.0212%	-0.0022%
LB_6	0.20%	-1.07%	-0.98% -0.98%	138.07	-0.0331%	-0.0076%
LB_20	0.21%	-1.08%	-1.00% -1.00%	140.35	-0.0342%	-0.0081%
LB_45	0.22%	-1.13%	-0.81% -0.81%	144.41	-0.0342%	-0.0066%
LB_90	0.22%	-1.23%	-0.83% -0.83%	159.01	-0.0364%	-0.0078%
LB_180	0.20%	-1.35%	-1.29% -1.29%	184.92	-0.0404%	-0.0088%

Source: own elaboration. Percentage variations and consumer savings are accounted in relation to the benchmark values.

The potential for consumer savings from the DR program grows as the number of time periods evaluated increases. The same happens for GDP levels. This is reasonable because the more time periods considered, the better the representation of electricity operation, the better the evaluation of more extreme electricity price levels, and consequently, the higher the incentives to apply load shifting or conservation. Even after considering the approximate 10% general equilibrium effect, the difference between the models' total economic savings is largely explained by the observed difference in prices.

The robustness of the model results increases substantially once we include a minimum number of time periods. This can be clearly seen by comparing the GDP and welfare measures for models with a small number of time periods, which present differences in the order of 50% to 250% (for LB-1 vs. LB-6), or with more time periods that achieve differences of only 10% to 18% for the GDP and welfare changes.

The results presented in Table 17 and in the previous sections show that the introduction of time periods in the CGE model improves substantially the representation of the electricity sector and of the electricity fuel supplier behavior, even when compared with an already detailed electricity technology CGE model.

However, we do not need to include a large number of time periods to achieve large differences: six seem to be enough to represent correctly the main macroeconomic effects of the policy evaluation[49]. In addition, 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 simulating up to 540 time period disaggregation levels[50] for a medium-sized country like Spain.

The load block disaggregation sensitivity analysis carried out on this and the next chapter is sufficient to show the proposed models feasibility and the model comparison results stability. However, extra precaution is advisable for the application of this thesis model in more policy centered publications. Extending the sensitivity analysis to include macroeconomic figures variations and elasticities ranges are crucial to validate the results obtained on simulations that aim to provide policy recommendations due to the non-linear character of the GEMED model formulation.

3.5 Conclusions

This chapter has presented an assessment of an electricity demand response program in Spain, by which residential consumers are exposed to real-time prices, and can react by shifting in time and reducing certain loads in their homes. Since this assessment requires the combination of features from bottom-up and CGE models, we have used for the first time a CGE model formulated with time period disaggregation, location and technological detail in the electricity sector.

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[49] More load blocks are only required under policies with more meaningful load shifts consequences.

[50] While the memory requirements of introducing more load blocks greatly increase, the marginal benefits tend to decrease after a certain number of load blocks.

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

Our results show a reduction in overall electricity demand, with conservation measures dominating load shifts. However, electricity prices increase (something that would not be observed with a bottom-up model). Carbon dioxide and atmospheric emissions decrease (due to the overall reduction in demand). Household welfare increases, as might be expected from a policy that tries to correct the provision of information to consumers, but GDP decreases because of the larger drop in producers' surplus caused by the contraction of demand. In fact, the policy, similarly to other energy-efficiency policies, creates a transfer of wealth from producers (who cannot adapt in the short term their generation portfolio to the change in demand) to consumers.

As pointed out along this chapter, the GEMED model is able to estimate indirect and general equilibrium effects, impossible to attain under a pure BU formulation. On the other hand, the electricity production decision is much better represented than in a conventional CGE model, as can be verified by the load shifting from peak units to baseload power plants, which could not be observed under a non-BU paradigm. In our application this was reflected by a reduction of the use of natural 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).

We also estimated a 6.5-11.2% potential indirect 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 of the use of electricity technologies and other fuel sectors variables in the order of 4.23% to -12.6% in both directions, even when compared to just a simple 6 time-period GEMED alternative. The fuel substitution, quantities used, price levels, and emissions consequences could be mistakenly estimated under a non-micro-founded and non-temporal-disaggregated CGE scheme.

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.

The main conclusion of this chapter extends the Sue Wing (2008) findings. The introduction of time differentiation on the electricity sector description extends even further the gap between the welfare results compared to single product top-down models with smooth production function representation. The importance of richer technology, time and location differentiated models such as GEMED, becomes crucial to evaluate correctly electricity policy assessments.

Nevertheless, the results obtained by this chapter 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 time period, 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, substituting the production function formulation for the corresponding MCP BU formulation presents as a clear research improvement. This requires moving to a completely integrated mixed complementarity hard-link hybrid TD-BU model.

This hybrid approach would also allow for a much more detailed representation of the BU model, in particular 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.

The following chapter will present the calibration procedure and equation formulation required for developing the hybrid alternative, and in particular, will apply the model to a real-world noteworthy tax evaluation policy in order to prove its tractability and feasibility.

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4 The H-GEMED Model

4.1 Introduction

As mentioned earlier in this thesis, choosing between exploiting the technological richness of BU models or the indirect effects evaluation of TD models can represent a significant commitment when dealing with complex policy assessments, like environmental issues for example. Undoubtedly, the detailed description provided by BU models of the set of technologies available is crucial in an analysis of operational and environmental impacts. On the other hand, as Böhringer and Löschel described, “energy policies do not only cause direct adjustments on energy markets but produce indirect spillovers to other markets” (Böhringer & Loschel, 2006, p.136).

The ambiguity in the modeling choice paradigm for E3 assessments emphasizes the failures of both independent BU and TD models to represent the linkages between the economic forces ultimately driving demand and production choices and their environmental consequences. This raised the necessity of pursuing alternative formulations capable of providing policy assessments for which individually neither TD nor BU grant a satisfactory analysis.

The previous chapters of this thesis provided an alternative to overcome partially these limitations by guiding the reader through building an electricity detailed CGE model that includes essential electricity attributes like technology, temporal and location detail. The GEMED model was then created.

The improved electricity product and generation representation allow GEMED to better evaluate electricity policy analysis when compared to other wide-spread TD alternatives, like the EPPA-MIT model (Paltsev, et al., 2005) or González-Ruiz de Eguino (2007). However, even GEMED is still a pure TD model, and by being so, it still represents the electricity behavior through the use of elasticities and economic production functions.

Elasticities used on the TD production representation are conventionally estimated from historical data and can represent a good approximation to stable production decision structures. But it would be naïve to assume that this is the case for the very own subject of a policy assessment, in which the policy by itself can substantially change the shape of the sector evaluated.

Moreover, the abstraction inherent in such economic production functions disregards important aspects from the physical production processes – including error, entropy or waste – and from the business processes – ignoring the role of management, of sunk cost investments and the relation of a fixed overhead to variable costs. Respecting the thermodynamic laws under an essentially economic framework and dealing with technologies retirement, evolution and backstop alternatives can represent a challenge even under the GEMED model formulation.

Much has been done to improve the CGE representation of elasticities and production functions in other to partially overcome these limitations. Kiuila and Rutherford (2013) for example tackle a related issue by estimating the elasticity from a piecewise-smooth approximation of the engineering bottom-up cost curve instead of from historical data. The estimation is capable of ex-ante considering an abatement function into a TD model, but their solution still implies the loss of the direct linkage between the electricity production decision and the stepwise engineering cost merit order representation. The stationarity of the elasticity estimation is a strong assumption which complicates the implementation of technological progress and ex-post alternative simulations not included a priori on the elasticity estimation.

This explains why iterative solutions came to the spotlight following Böhringer and Rutherford (2006) publication. EPRI's US-REGEN, CRA's MRN-NEEM and MIT's USREP models are among the examples that followed the "soft-linked" models trend closely. However, under this approach not all the dual information is shared between models, what could lead to an incomplete policy assessment. Inconsistencies in behavioral assumptions between models can cause convergence limitations, common for example on the different behavior found on TD and BU formulations for emissions markets price estimations. Also, different cost structures, diverse data sources (company accounting vs. technical characteristics) and data availability difficult the communication between both modelling paradigms.

One further step was still required to build a better electricity policy assessment tool. To build a single model that incorporates in unison a detailed production description of the policy assessment crucial sectors and, at the same time, represent their interactions with the whole economy. The so-called “hard-linked” hybrid model framework.

Such goal was partially achieved by models that included a reduced form representation of either the BU or TD model in the other one (eg., Messner & Schrattenholzer (2000), Stratchan and Kannan (2008), Manne et al. (1995), Bosetti et al. (2006), Sarica and Tyner (2013) and Proença & Aubyn (2013)). However, none of these models addressed the inherent complications related to considering a comprehensive temporal disaggregation of the electricity product and the existence of complex BU modeling constraints, crucial to a detailed assessment of electricity policies.

Even after Böhringer and Rutherford (2008) presented the theoretical basis for the BU-CGE hard-link model implementation, its non-reduced “hard-linked” form seemed to lie at an unattainable abstraction level. This modelling framework potential was therefore only partially achieved by the literature until now.

This chapter intends to prove that it is not only feasible to achieve a more thoughtful energy analysis by considering simultaneously BU and TD features, but also to present a model that does apply fully the hybrid paradigm, the Hybrid General Equilibrium Model with Electricity Detail (H-GEMED). H-GEMED is a mixed complementarity model that embodies simultaneously both CGE and a power generation operation and expansion model behavioral equations.

With that goal in mind, section 4.2 describes the hybrid hard-linked electricity bottom-up and CGE top-down model formulation. Section 4.3 introduces a current policy issue question to be assessed on section 4.4. This relevant policy is used to demonstrate the potential and feasibility of using the hybrid model for energy policy evaluations. Section 4.5 presents some conclusions and research extensions derived from this work.

4.2 Model Formulation

H-GEMED (Hybrid General Equilibrium Model with Electricity Detail) is a mixed complementarity model that embodies simultaneously both GEMED and a hydro-thermal power generation operation and expansion model through combining them Karush-Kuhn-Tucker conditions into a single non-linear equilibrium problem.

The model is capable of representing entirely all the features present in the TD and BU approaches, improving its application for electricity policy assessments.

The replacement of the statically estimated production function representation for the electricity generation production decision overcomes the remaining limitations still present in the GEMED model formulation. The model can therefore represent explicitly thermodynamic properties, technology evolution and detailed operation constraints, between other improvements.

Back-stop technologies, stepwise cost structure, abatement curves, learning-by-doing endogenous evolution, sector spillovers, demand and income rebound effects, change in frontier competitiveness, inputs and consumption behavioral substitution can be all evaluated simultaneously and endogenously with such an instrument without compromises when compared to a pure BU or TD simulation.

Nevertheless, a few steps are necessary to achieve the goal of creating the H-GEMED model. Most of the requirements were preliminary introduced in previous chapters, but some need to be revisited and extended to answer to the specific demands of a truly hybrid model.

Firstly, it is necessary to define which components (models) are part of the hard-linked hybrid model and the mathematical mechanism used to join them. Secondly, the compatibility between their data sets must be assured in order to be able to apply the model to a real policy evaluation, which can be used to prove its feasibility, strengths and limitations.

4.2.1 The model components and the mathematical formulation

The first step for building a hard-linked hybrid model is to define the model components most relevant to the aimed analysis.

As previously described in chapter 1, CGE models are the most used modelling approach on TD energy-economics assessments. The GEMED model, introduced on chapter 0, presents a clear advance over these models by overcoming most of the incompatibilities between the micro and macro foundations found on TD and BU formulations. Besides, GEMED already introduces a much deeper electricity detail in the description of the demand and production decisions. Naturally, this chapter chose to use the GEMED model as the TD component of the hybrid formulation.

Following the same "popularity" rule for E3 assessments, the BU model chosen follows the MARKAL/TIMES (Fishbone and Abilock, 1981 and Loulou et al., 2005) and MESSAGE (Messner and Strubegger, 2001, and Keppo & Strubegger, 2010) family. Nevertheless, the BU electricity model used is a hydro-thermal power operation and expansion model based on Ventosa (2001). The BU model used is better detailed than the typical E3 BU electricity alternatives by presenting a bigger temporal and technology granularity. Besides, it can be relatively easily extended to incorporate possible oligopolistic behaviour of the firms (Linares et al., 2008).

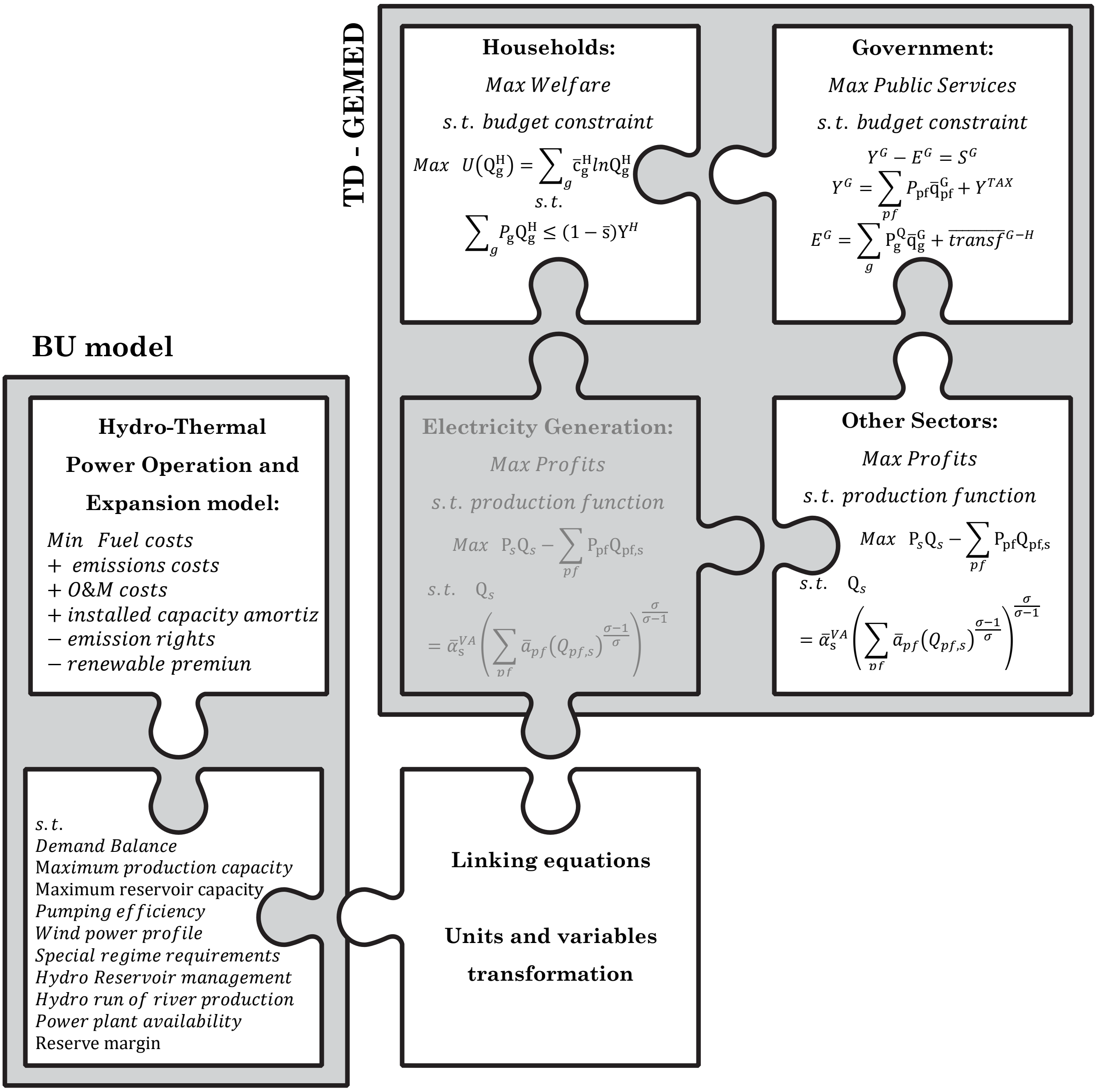
Once the model components are defined, the mathematical formulation of the hard-link must be defined. A schematic representation of the hybrid model components can be seen on Figure 6.

As mentioned briefly before, the integration of both TD and BU models is achieved by writing their equations simultaneously into a single non-linear equilibrium problem in the Mixed Complementarity Problem (MCP) format (as described in Böhringer and Rutherford, 2008).

Following chapter 2, the GEMED model is already defined under a mixed complementarity formulation. Different agents' decisions – government, households, productive sectors – are individually represented by their respective optimal consumption and production decisions – maximize utility, maximize profits and so on. The link between these different agents is made through the product and factor markets and an economic equilibrium is reached once the prices and quantities satisfy all agents' optimal decisions.

As each product sector is explicitly represented through their individual MCP equations, it is straightforward to assume that the optimal production decision for the electricity generation activity could be replaced by an even more complex representation. The typical statistically-based economic production function representation of the electricity activity can therefore be substituted by a more extensive engineering representation of the activity. That is exactly where the BU model enters the game.

Figure 6. Schematic representation of H-GEMED model components.



Source: own elaboration.

The set of electricity generation equations of the GEMED model, the gray piece on the puzzle center in Figure 6, is removed from the model under the hybrid formulation. Its “puzzle piece” is then replaced by the BU model equations that describe the electricity generation activity.

In order to achieve that two steps are required.

First, the BU model must be formulated also in the MCP format. The mixed complementarity version of the hydro-thermal power operation and expansion model used on this thesis is presented in Annex IV (equations AIV.4-1 to AIV.4-18).

Second, a few additional constraints are necessary to translate the units and variable correspondences between the BU and TD formulations. Annex VI (equations AVI-31 to AVI-44) present the required equations.

After replacing the GEMED original electricity generation sector equations with the above described mixed complementarity conditions, the mathematical formulation of the hard-linked H-GEMED model equations can be considered complete[51].

The resulting hybrid model offers a wide range of advantages in electricity policy assessments. First of all, from the BU model perspective, parameters that were previously exogenous become endogenous variables of the model. The total electricity demand profile becomes a direct result of other agents' endogenous decisions of production and consumption; the fuel prices and product availability are determined according the interaction between national and foreign suppliers and demanders; the operation and maintenance costs are susceptible to the increase or decrease of the country labor cost; the investments amortization is affected by the capital price; and so on.

Second, from the TD perspective, the electricity production decision complies with several constraints to better represent the competitive generation market and the different policies that could affect it. The electricity price definition approaches the actual observed behavior by departing from the average representation to a marginal-price competitive electricity market settlement; investment amortization burdens are considered in the production decision and technology utilization; operational constraints, ever more important for the electrical system due to the increase intermittence of production sources, can be much better represented endogenously to the model; and so on.

4.2.2 The model calibration

Once the model is defined it remains still to define the dataset necessary to execute it. The H-GEMED data requirements are the same as the ones found for using the GEMED model. The detailed description of the data requirements can be found in

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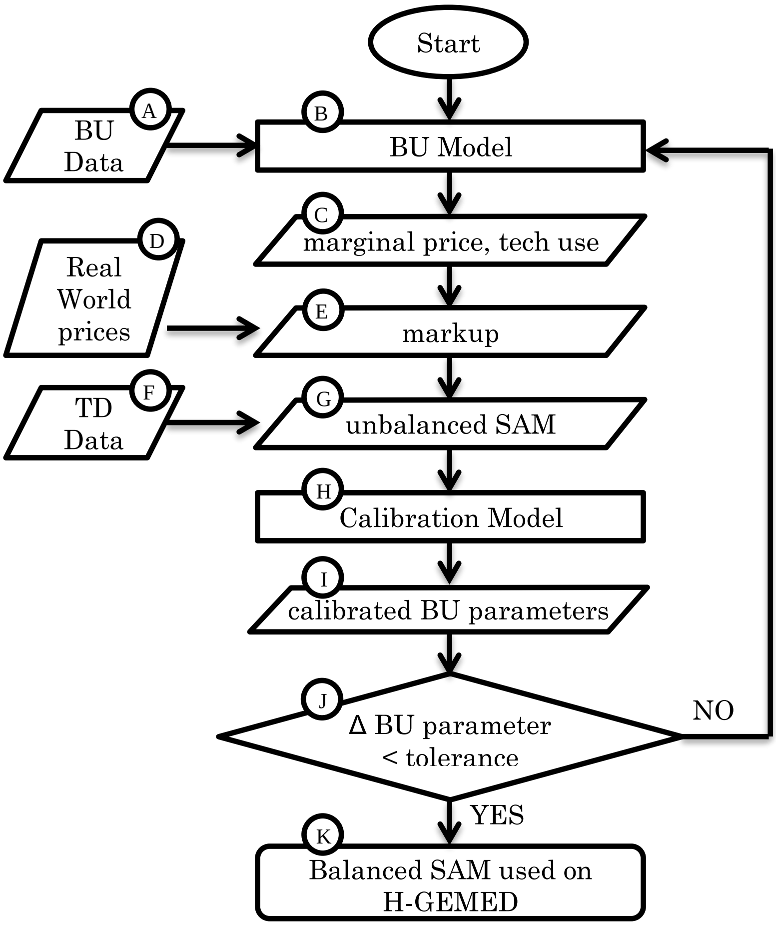
[51] The complete description of the hybrid H-GEMED equations can be found in Annex VIAnnex VI.

section 2.3. However, additional care must be taken to ensure the compatibility between the TD and BU data when applied to the hybrid model.

As previously described on chapter 2, a goal programming calibration model was used to achieve a compatible and micro-founded dataset to use with the GEMED model. However, the sequential calibration algorithm described in Figure 2 (chapter 2) needs to be refined in order to deal with the more complex hybrid model requirements.

Figure 7 summarizes the algorithm used to achieve a SAM calibrated matrix compatible with both TD and BU modeling data assumptions that can be used in our hybrid model formulation.

Figure 7. H-GEMED calibration process flowchart.



Source: own elaboration.

The BU model is the starting point of the calibration process. The original BU data (Figure 7, A) is used by the electricity operation and investment model (Figure 7, B) to provide the optimal electricity generation decision – marginal price, technology use, water reservoir schedule, investments decisions, and so on (Figure 7, C).

Once the BU results are obtained, it is possible to calculate the distribution of fixed costs payments between the different electricity load blocks. By comparing the results obtained with real world data (Figure 7, D) it is also possible to estimate the markup term and the portion of costs non-accounted by the model's simplified representation of the real world (Figure 7, E).

Joining the TD data for the economy (Figure 7, F) with the just acquired BU data for the electricity production and demand, we are able to build an unbalanced SAM (Figure 7, G) which contains both TD and BU data information.

We then apply the calibration model (Figure 7, H) to balance the SAM. The model aim is to reproduce exactly the macroeconomic magnitudes observed at the benchmark year by adjusting the technological BU parameters (Figure 7, I). Indeed, the calibration model used by the hybrid formulation is no different from the one applied to the GEMED model[52]. However, an additional iterative step is required in order to ensure the perfect compatibility between the TD and BU model components.

The BU results obtained in step C (Figure 7) are derived from the original BU parameters. But, what if the calibrated BU parameters provide a different optimal result for the electricity activity when fed back to the BU model?

This is not a strong restriction when considering the pure TD model case, as the data set obtained on the first calibration iteration provides a perfectly balanced SAM, suitable for building a model like the GEMED. However, under the hard-linked hybrid alternative the entire BU model is part of the final model equations. Therefore, an incompatibility between its results and the calibrated balanced SAM would provide an invalid initial point to the simulations.

For example, under a high discretization level of power plants even a small change of the thermodynamic efficiency due to the calibration process could promote a cost merit order change. If that were the case, the BU model would be incapable of perfectly reproducing the calibrated SAM expenditures, making the initial benchmark point invalid.

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[52] More detail about the GEMED calibration can be found in section 2.2.4.

Therefore, the hybrid model calibration procedure requires an additional iterative step to ensure that the BU optimal solution and the SAM benchmark point are in perfect sync.

An additional step is added to the calibration process to test the convergence between the previous and actual iteration results (Figure 7, J). If the difference is less than a pre-defined tolerance, the data calibration is considered achieved and the balanced SAM can be used as a perfect compatible data set for the H-GEMED model. If the error is higher than the tolerance, the calibration process is restarted using as departure point the newly calibrated parameters (Figure 7, B).

The existence of at least one calibrated technology parameter for each SAM variable and the fact that both the calibration and the BU models can be represented as linear optimization models allowed our tests to reach a convergence point without much complications[53]. Also, the addition of further technical calibration constraints, like the equation enforcing merit order presented on chapter 2 (section 2.4), greatly increases the chance of achieving a final calibrated SAM with the minimal amount possible of iterations.

Once the convergence is reached, the same dataset can be used on the BU, TD, GEMED or H-GEMED models without any inconsistencies. We are finally able to apply the model to an actual policy assessment in order to prove its feasibility, strengths and limitations.

4.3 Case study: Green Tax Reform

As pointed out by the IEA recent special report on energy and air pollution: “Clean air is vital for good health. Yet despite growing recognition of this imperative, the problem of air pollution is far from solved in many countries, and the global health impacts risk intensifying in the decades to come”. (IEA, 2016, p. 265).

Under this situation, green tax reforms have gained a lot of policy traction recently. They are considered both as an opportunity for correcting market imperfections, through the internalization of previously unaccounted environmental and health

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[53] Although the BU electricity model used in this thesis has a corresponding linear formulation, nothing forbids the use of a non-linear model for the BU component of the hybrid model. Further research should be pursued to explicitly describe the conditions necessary to the calibration convergence existence, especially for the non-linear case.

externalities, and for providing a new source of tax revenue to governments, without carrying the usual negative public repercussions of such policies. Such reform is usually related to the idea of obtaining a double dividend because of the environmental (reduction of air pollutants emissions) and welfare gains (lowering the effects of more distortionary taxes) (Pearce (1991), Repetto et al. (1992)).

An atmospheric pollutant tax can provide the correct economic signals for agents to change their behavior, by taking into account their environmental and health consequences. Such tax acts directly under the consumption and production decision, providing incentives to replace consumption patterns or to adopt newer and cleaner production methods, thus lowering the negative consequences of air pollution. But what would be their expected efficacy level?

To evaluate an atmospheric pollution tax policy implementation ex-ante it is necessary to take into account the diverse emission sources and the agents affected by this policy and the geographical dimension of the air pollution consequences.

On the source subject, energy use and production are the single most important source of particulate matter, sulfur oxides and nitrogen oxides emissions. Diverse agents can be included as the more meaningful contributors for that, underlining the energy sectors, and in special the electricity sector, the transportation sector and the final consumers' demand behavior.

On the location subject, different atmospheric pollutants can cause effects on diverse dimension levels. From the local level, like air quality that can be highly influenced by small particles, sulfur and nitrogen oxides, to the global level, like global warming or ozone layer degradation influenced by CO2 emission gases or CFCs.

The mainstream literature repeatedly adopted the use of TD models for the evaluation of such policies, and more specifically general equilibrium models (CGEs), because of the above mentioned dimensions of the problem. However, this choice did come with important tradeoffs.

Take for example the Spanish case. The electricity sector alone is responsible for approximately 70% of the SO_2 and 23% of the NO_x emissions in the base year used on this thesis[54]. As explained in chapter 2, traditional CGE models usually lack the desirable level of detail necessary to correctly describe the electricity sector operation. They also lack a good description of peakier technologies and an inadequate marginal price representation which are crucial for a policy evaluation such as this one. Besides, the geographical production location within the country is usually disregarded under the CGE traditional formulation.

The BU model alternative could in turn present a better discretization of geographic electricity production decisions by including multiple nodes and better description of marginal price and technology specificities. However, what about the other 30% SO_2 and 77% NO_x emission sources? And what if demand could also play an important role in the policy evaluation and not only the production decision?

A perfect opportunity is then created to use the H-GEMED model for a relevant policy evaluation. In the next section we intend to present the consequences of a Spanish green tax reform focused on local air pollution and present the hybrid model advantages when dealing with this policy assessment.

4.3.1 Policy definition

The economic situation of countries like Spain deteriorated significantly over the last few years. This forced the government to search for alternative policies that may foster economic growth. Contradictorily, during this time the Spanish labor taxes have increased while the green tax revenue has fallen, to 1.6% of GDP in 2012, achieving levels much lower than the European average, 2.4% of GDP (OECD/EEA, 2015).

Under this scenario, a green tax reform has gained the spotlight in recent Spanish policy discussions (Labandeira et al. (2014) and Gago et al. (2014)). This tax instrument could be used to internalize environmental externalities, correct existent distortionary taxes and provide additional government revenues to act upon key economic variables.

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[54] The data and results obtained on this chapter should be carefully considered for actual policy recommendations because the base year used for the macroeconomic data on the model is 2005. This does not mean any compromises for this thesis objectives as this chapter intends to demonstrate the application of the hybrid model formulation for relevant policy assessments. Further research is being under way using the same methodology to update the data and providing a more suitable and actual policy recommendation.

The simulation presented on this chapter aims to assess the potential and consequences of a green tax reform in Spain. As underlined by the recent Economics for Energy report (2014), Spain presents a significant lack of regulation for NO_x and SO_2 emissions when compared with European countries. These emissions are strongly related with urban health issues, smog air pollution and acid rain. This pollution form is a present-day important concern in Spain and can be easily attested by events like the fact that in 2015 Madrid declared for the first time transport restriction measures to control smog air pollution.

According to the IMF (Parry, Heine, Lis, & Li, 2014), estimates for the actual externalities related with these emissions can reach very high levels, up to 10,500 €/ton of NO_x and 8,000 €/ton of SO_2. Denmark applies a tax of 3,427 €/ton on NO_x and of 1,492 €/ton on SO_2. We choose to introduce a conservative emissions tax level for both pollutants of 1,000 €/ton to partially correct the environmental externalities of the productive sectors, households and transport emissions.

The direct effect of this tax introduction at the electricity level is the loss of competitiveness of fossil fuel related power production. It is expected that coal power plants would suffer the more meaningful retraction because of their sulfur and nitrogen oxides emissions, while gas-based power plants would come in the second place because of their nitrogen emissions. However, the final consequences could only be only assessed if we add to the equation possible capacity restrictions and operation constraints which could limit the replacement of these more emitting technologies. This is where the BU model detail comes in handy.

As already mentioned, the contribution of the remaining sectors to these atmospheric emissions could not be disregarded on this policy evaluation. The TD model component is crucial to evaluate for example the consequences on transport demand and other energy producers' production decision changes due to the introduction of the tax reform.

Moreover, the policy assessment would be incomplete if we do not consider the effects of the tax revenue recycling on the economy. The TD component of the hybrid model allows the investigation of the different alternatives for the allocation of the green tax reform revenues in the economy. These effects are directly related to the double dividend environmental taxes outcomes. Table 18 summarizes the different simulations scenarios used on this work.

Table 18. Green Tax Simulation Scenarios.

Tax	Tax revenue allocation		
1000 €/t SO_2 1000 €/t NO_x	Government Budget	Social contributions subsidy	Productive sectors lump sum

Source: own elaboration[55].

The tax revenues obtained through the green tax reform are analyzed under the perspective of alleviating the government budget, reducing the labor tax levels to foster employment, or reinvesting the income as a lump sum payment to improve the financial situation of the productive sectors according to their final output levels.

4.4 Results

The model was executed under the different load block disaggregation described in chapter 2 (Table 6) to confirm the stability of the simulation results and to provide a sensitivity analysis to the policy outcomes. Since the H-GEMED model is nonlinear, that exercise guarantees that the simulation does not present multiple local optimal equilibrium solutions in the vicinity of the evaluated policy in order to validate the results obtained.

The introduction of the green tax reform allows for a rearrangement of the existent taxation structure of the Spanish economy, but the effects are highly dependable of the green tax income destination. The total tax revenue is in the order of 1,825.96 million euros, 561.63 million from the SO_2 tax and 1,264.33 million from the NO_x tax.

The policy achieves a higher reduction of SO_2 emissions (~34%) when compared to NOx emissions (~5%). In order to understand better the emission effects, it is necessary to evaluate the policy consequences for each economy sector.

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[55] The taxes follows the emissions externality cost levels applied on the Economics for Energy (2014) special report on energetic and environmental taxes.

As can be seen in Table 19, the green tax reform promotes a meaningful reduction of the pollutant emission levels both on the electricity sector and the rest of the economy. However, the big pollutant emissions found on the electricity sector and the better substitution effects represented by the model clearly underline the biggest role of this sector to the policy consequences when compared to the rest of the economy.

Table 19. H-GEMED productive sector and household emissions impact.

	Pollutant	**Government Budget**	**Social contributions subsidy**	**Productive sectors lump sum**
Electricity	SO_2	-60.53%	-60.53%	-60.86%
	NO_x	-25.82%	-25.82%	-25.95%
	CO_2e	-23.17%	-23.17%	-23.30%
	PM_{10}	-53.64%	-53.64%	-53.93%
Manufacturing	All[56]	0.14%	0.01%	0.06%
Coal		-39.29%	-39.30%	-39.52%
Oil-Nuclear		-1.32%	-1.29%	-1.14%
Gas		21.28%	21.29%	21.43%
Transport		-0.56%	-0.56%	-0.55%
Other_Services		0.01%	0.06%	0.04%
Households		-0.24%	-0.04%	-0.02%

Source: own elaboration.

If we take a closer look at the electricity sector (Table 20), we can observe that the introduced tax causes a loss of the competitiveness of coal fired power plants, with a consequential replacement by CCGT power plants.

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[56] The H-GEMED model estimates the emissions for the electricity sector based on the technologies and fuel used to supply the electricity, providing additional detail to the different emissions. All other sectors have simpler emissions estimations based on the final production levels because the lack of detail in the sector specific technology description. Therefore, the non-electricity sector emission sources present a single emission variation for every pollutant emitted by the production and consumption process.

Table 20. Annual electricity production for the government budget simulation.

	Benchmark		Green Tax Reform		Variation
	GWh	%	GWh	%	%
Nuc	55195	22.18%	55195	22.20%	0%
NCoal	60273	24.22%	19838	7.89%	-67.09%
ICoal	13555	5.45%	10966	4.39%	-19.10%
CCGT	68580	27.56%	103009	41.56%	50.20%
F-G	1809	0.73%	871	0.33%	-51.85%
Hyd Res	9311	3.74%	9311	3.74%	0%
Hyd RoR	5418	2.18%	5418	2.18%	0%
Wind	21861	8.79%	21861	8.79%	0%
ORSR	7116	2.86%	7116	2.86%	0%
NRSR	5593	2.25%	15037	6.05%	168.85%
Pump	93	0.04%	17	0.01%	-81.72%

Source: own elaboration.

Coal fired power plants that use as fuel Spanish coal, with lower quality and high sulfur content, suffer a 67.09% production contraction in peak hours due to its loss of competitiveness because of the extra SO_2 and NO_x tax payments. Imported coal fired power plants also suffer the same effect to a lower degree (19.1% production contraction to their previous production levels). Consequentially, CCGT power plants increase their electricity production share filling the supply gap. The fuel replacement also explains why the NO_x emission reduction is not as efficient as the SO_2 emissions reduction, as the natural gas use increase curtails part of the emission reduction due to its nitrogen content.

Other peak technologies with lower utilization are also greatly affected by the increase of costs coming from the more restrict emissions policy. Fuel-gas peak power plants and pumping unit alternatives lose more competitiveness than cogeneration power plants (NRSR) in supplying the higher demanding electricity load hours of the year.

Two fuel supplier sectors, coal and gas, are directly affected by this shift in the electricity sector optimal production. The coal sector suffers an important contraction, while the natural gas demand increases by acting as a substitute fuel. An important side effect can be noticed with the meaningful CO_2-equivalent emission reduction promoted by the retirement of coal fired power plants.

Other sectors are also affected by the policy but with smaller consequences. The demand change of petroleum-derived fueloil used on the Fuel-Gas units is very low in relation to the oil refining sector magnitudes to cause substantial price repercussions to the economy. Manufacturer industries and services are not substantially affected by the policy, while the households and the transport sector are negatively affected by the pollutant added taxes, higher electricity prices, and specific fuel costs observed when reducing their emissions levels.

The total reduction of atmospheric pollutant emissions (Table 21) provides the most direct benefit of the proposed policy, the first dividend. However, the tax revenue obtained by the environmental tax can also be used to improve even more the policy welfare gains. The policy double dividend resulted from the allocation of the green tax reform revenues in the economy is highly dependent of the method chosen.

The GDP variations are relatively small because of the policy size. As expected, a tax introduction represents a distortion from the initial benchmark equilibrium causing a contraction of GDP as a direct result of the model assumptions. Nevertheless, the most important feature to observe is the relative difference between the different options of applying the additional tax revenues from the environmental tax.

The decision to improve the government budget deficit allows a better financing of the government debts and increases the external transfers. This improves the country situation in the long run, effect not captured by the static model used. The national market faces a short-run contraction as can be seen by the lower GDP levels. Although all alternatives present similar GDP levels, it is the lump sum transfers to the productive sectors that shows the biggest economy contraction[57].

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[57] Test scenarios were the green tax revenue income replaces more distortionary taxes could represent an interest future research extension to simulate the double dividend assumption potential.

Table 21. Green tax reform H-GEMED macroeconomic variations.

		Government Budget	**Social contributions subsidy**	**Productive sectors lump sum**
GDP		-0.08%	-0.08%	-0.09%
Wages		-0.20%	0.21%	0.00%
Emissions	**SO_2**	-33.79%	-33.81%	-33.96%
	NO_x	-5.34%	-5.35%	-5.35%
	CO_{2e_ETS}	-12.64%	-12.68%	-12.72%
	$CO_{2e\_non\_ETS}$	-0.12%	-0.09%	-0.07%
	PM_{10}	-9.38%	-9.37%	-9.39%
	CO	-0.09%	-0.05%	-0.02%
	VOC	0.16%	0.07%	0.11%
	NH3	0.13%	0.01%	0.05%

Source: own elaboration considering 120 time-differentiated electricity products.

The general equilibrium model used does not include an explicit employment representation. Nevertheless, the average wage can be used to provide a good indication of the policy consequences for reducing unemployment and increasing the labor force welfare, as the labor demand does not suffer substantial changes.

Our results show that the decision on how to use the revenue obtained from the tax plays an important role on the labor market. The social contributions subsidy scenario provides a substantial improvement of labor conditions (wage increases 0.21%). Meanwhile, the policy can be made innocuous to the wage economy levels if the emission tax revenue is reapplied to the productive sectors as lump-sum transfers. About the government budget scenario alternative, again, the long run benefits of the budget deficit control are not included on this thesis static model evaluation and the government budget represents the worst short run result from the point of view of reducing the wages level of the economy.

The advantages of using the H-GEMED model for assessing this policy are clear once the results are evaluated. The electricity sector detail provided by the BU model component is crucial to describe the incomplete replacement of more polluting generation technologies in favor of cleaner ones, which in turn only partially achieves the policy objectives for NO_x emissions reduction. On the other hand, the TD model component allowed to represent a much more discrete reduction of the emission levels on the other economy sectors when compared to the electricity generation activity. This is due both to the lack of short run technology alternatives to the dirtier production structure of the other sectors, and the presence of rebound effects that are even capable of indicating an increase on other gas emissions, like VOC and NH_3, as a side effect of the policy.

4.5 Conclusions

Low environmental taxation and a high demand for internalizing pollution externalities places Spain in a unique position for considering the application of a sustainable green tax reform policy. This chapter has presented an assessment of a tax on SO_2 and NO_x emissions and its consequences to the Spanish economy. Controlling these emissions is extremely important to reduce local pollution and increase air quality in cities and at regional levels.

Since both pollutant emissions are highly related with the electricity production technologies the policy assessment required a good representation of electricity sector production decisions. Meanwhile, the taxation estimation and its economic consequences clearly present an economy-wide nature and important repercussions across the economy, advocating in favor of using a general equilibrium model instrument. Applying the hybrid TD and BU framework on this policy evaluation presents itself not only as a perfect opportunity, but even a necessity to correctly assess the policy.

The main contribution of this chapter is to present an innovative hybrid model built especially for electricity policies assessments. This chapter has presented the methodology necessary to determine the calibration procedure and the equations formulation in order to build the H-GEMED. The green tax policy assessment carried out demonstrated the feasibility and capabilities of using such modeling instrument in real-world and noteworthy policy evaluations.

H-GEMED is a hybrid general equilibrium model that is composed simultaneously by a TD CGE model and a BU electricity hydro-thermal electricity operation and investment model. Both models are made compatible through the presented iterative calibration methodology, and their equations are solved simultaneously as an MCP. As a result, electricity production and demand decisions are comprehensively represented with the inclusion of time, location and technological detail and the economy repercussions are evaluated endogenously by the general equilibrium feature of the model.

Our results show that approximately 2,386 million euros could be collected by the government with a relatively small SO_2 and NO_x tax level. As expected, the atmospheric emissions of both gases decrease but it is on the SO_2 emissions that the biggest contraction is observed. A policy like this will have of course significant effects on the electricity sector. Coal is substituted by natural gas, which mitigates the NO_x emissions reduction, most especially on the electricity sector where the coal fired power plants lose competitiveness to CCGT power plants. Fuel provide sectors - Natural gas and coal - are directly affected by the changes on the electricity sector. Manufacturer industries and services are not substantially affected by the policy, while the households and the transport sector reduce slightly their total emissions.

It is also shown that the macroeconomic policy consequences are highly dependable of the tax revenues allocation. Improving the labor conditions by redirecting the tax revenues into improving the social contributions results on a substantial improvement at the labor market situation. Meanwhile a government budget deficit finance or a lump sum productive sector transfer can serve for other macroeconomic objectives in the longer term.

Still, there is still much field for improvement both in the policy evaluation and the model presented on this chapter. Work has being done to include diffuse CO2 atmospheric emissions, energy taxes and renewables promotion measures in the green tax reform assessment to provide a more comprehensive policy recommendation. Also, this thesis policy assessments were built upon a data set that is being updated to reflect a more current situation.

On the model perspective, the H-GEMED can be easily extended to include a dynamic recursive behavior allowing to simulate evolution paths of the policies proposed. European targets, backstop technologies, learning-by-doing effects, and a large extent of technology detail can be included in order to improve the electricity sector representation. The production structure of non-electricity sectors can be extended and incorporate better estimations of substitution elasticities and abatement technologies. The electricity demand can be more comprehensively described through the use of electricity services and by the inclusion of different agent income levels and energy consumption behavior.

Finally, there is no reason to restrict the inclusion of the improved production and demand representation exclusively to the electricity sector. The same process presented on this thesis can be used to extend and improve the representation of other economic sectors and products inside a general equilibrium framework, according their importance for the policy to be evaluated.

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5 Conclusions

This thesis aimed to develop a novel policy evaluation instrument suitable to assess simultaneously both macro and micro economic perspectives of electricity policies evaluations.

The component chosen to represent the TD macroeconomic behavior was a CGE model. These models are wide adopted on E3 modeling literature and present very important virtues for the representation of indirect substitution, income and rebound effects in economic systems. The BU component is represented by a hydro-thermal operation and investment electricity model, which provides a very good detail level of the electricity production and a good approximation of the behavior of competitive electricity markets.

With the goal of improving the economy-wide electricity policy assessment instruments in mind, the **first main objective** of this work has been to achieve the **reconciliation between the BU and TD data** frameworks.

Chapter 2 presented the calibration procedure responsible to fulfill this objective. For the first time in the literature an electricity temporal disaggregation was built into a SAM accountability scheme, while keeping technological detail. The obtained SAM electricity accounts are a direct result of micro founded BU technological parameters, increasing the policy application range of SAM based models. Temporal data (electricity load block levels), location characteristics (different electricity nodes production and demand structures) and technological disaggregation were introduced directly into the TD macroeconomic data framework.

In this regard, methodological improvements over existing technology-rich SAM calibrations were introduced as secondary thesis objectives. Our results showed that the minimax model proposed on chapter 2 consistently bests the commonly-found in literature quadratic alternative in terms of the maximum deviations obtained for the calibrated parameters.

The direct calibration of technological parameters instead of using expenditure shares also proved to provide important advantages on keeping the linkage between the calibrated values and the real world physical characteristics. This allowed both for the introduction of relevant physical constraints to the calibration problem, like thermodynamic limits and the preservation of the calibration merit order cost, and the extension of the resulting SAM dataset range of applications to a wider range of policy evaluations that could deal with features like technological evolution and learning-by-doing processes.

Finally, we have shown that the electricity-enriched SAM data could be applied to a complex country national accountability scheme and under a significant number of electricity load blocks, answering to the common data complexity criticisms of other authors on adopting such approach.

Once a compatible data framework was achieved, the **second main thesis objective** was achieved: **develop** a CGE model capable of including the richer SAM information and reproduce correctly the electricity demand and price behavior in competitive wholesale markets: the **General Equilibrium Model with Electricity Detail (GEMED)** was presented.

GEMED is an electricity micro-founded CGE model. The novelty of the GEMED lies in two major aspects: the disaggregation of the electricity sector to include temporal, location and technology detail; and the introduction of the possibility for agents to react to time-varying prices under technological constraints. This attribute is particularly important in policy assessments that include load shifting, demand profile changes and technology substitution.

GEMED is capable of combining features from both BU and TD models. It evaluates simultaneously optimal decisions for multiple productive and demanding sectors of the economy and it provides a detailed technological and time dependable behavior for the electricity production and demand decision.

The resulting model mimics the rich description of the electricity sector production decisions present in the BU electricity models while at the same time account for the indirect effects and inter-sectorial and institutional consequences of the energy policies assessed, impossible to attain under a pure BU formulation. Effects like electricity load shifting which could not be observed under a non-BU paradigm can be endogenously simulated on the GEMED.

A relevant policy assessment was carried out presenting two important secondary objectives: evaluating the policy results and confirming the feasibility of GEMED application. The model was applied to electricity demand response program in Spain, by which residential consumers are exposed to real-time prices and can react by shifting in time and reducing certain loads in their homes.

The policy features demanded the consideration of both BU and TD characteristics which indicated the GEMED recommendation on the policy assessment. Our results clearly endorsed this thesis hypotheses by showing that the BU evaluation could undermine the DR desired results because of an estimated 6.5-11.2% potential indirect effect not accounted by such models. Meanwhile the fuel substitution, quantities used, price levels, and emissions consequences could be mistakenly estimated by the order of 4.23% to -12.6% (Table 16) under a non-micro-founded and non-temporal-disaggregated CGE scheme because of incomplete technology information.

Nevertheless, the GEMED developed on chapter 0 was still susceptible to improvements. For example, the use of econometric production functions for representing the electricity sector behavior and the lack of detailed operation constraints on the technologies description could still act against a more comprehensive policy simulation.

Therefore, the **third** and most important **main thesis objective** was achieved. The formulation of a **Hybrid General Equilibrium Model with Electricity Detail (H-GEMED)**.

H-GEMED is a hard-link hybrid model that is composed simultaneously by the mixed complementarity conditions of both a BU hydrothermal electricity operation and investment model and a TD Spanish country CGE model. The resulting model (chapter 0) is capable of endogenously representing the retirement of non-competitive technologies, the inclusion of backstop technologies, technology specific operation constraints, stepwise cost structures, abatement curves, learning-by-doing endogenous evolution, sector spillovers, demand and income rebound effects, change in frontier competitiveness, or inputs and consumption behavioral substitution, among other effects unattainable without compromises on the previous evaluated modeling frameworks.

The calibration procedure developed on chapter 2 was revisited and extended to include a perfect compatibility between the BU and TD components. Besides, all information necessary to define the H-GEMED model components and formulation were presented on chapter 0.

A relevant secondary objective was fulfilled by evaluating the model under a real-world emission tax policy evaluation. This evaluation served the purpose of attesting the feasibility and show one of the potential uses of the hybrid modeling alternative. A green tax reform simulating the introduction of SO_x and NO_x taxation was assessed in the Spanish economy and the macroeconomic consequences were evaluated under different tax revenue allocation alternatives.

The economy wide tax policy repercussions and the importance of the technologies displacement effects observed in the policy results clearly advocates in favor of the advantages of using the hybrid model formulation when compared to pure TD and BU alternatives.

Even so, this thesis does not even get closer on exhausting the electricity hybrid modeling topic and many **future research topics** can be highlighted, both on the policy evaluation and the models' perspectives. Three main future research lines can be underlined: improve the electricity sector representation in the hybrid model; extend the TD model formulation; and apply the hybrid formulation to other sectors and economy agents.

The first research line focus on increasing the model capability of representing even better electricity focused policies. At the production side, the inclusion of backstop technologies and learning-by-doing effects, extending the power plants and technology disaggregation, dealing with high wind penetration representation and adding energy storage description can be proven essential to widen the model application areas. At the demand side, the potential of representing energy demand as different services, the differentiation of energy demanders by income and/or location, and the inclusion of relevant newer demand technology alternatives like the electric vehicles penetration are important subjects to be taken into account.

The second research line is the improvement of the TD model used on the hybrid formulation. Most of the extensive TD literature on CGE models extensions can applied and tested under the hybrid model alternative. The H-GEMED model can be, for example, extended to include a dynamic recursive behavior allowing to simulate policy evolution paths, European targets, introduce imperfect competition, improve the labor market representation and extend the model to deal with a multi-country/region formulation. The production structure of non-electricity sectors can be also improved and incorporate better estimations of substitution elasticities and abatement technologies.

Finally, there is no reason to restrict the inclusion of the improved production and demand representation exclusively to the electricity sector. The same process presented on this thesis can be used to encompass and improve the representation of other economic sectors and agents inside the general equilibrium framework, according their importance for the policy to be evaluated.

Additionally to these three main future research areas, one can cite a huge number of policy assessments that could take advantage of the instruments developed on this thesis: transition to time of use electricity tariffs and smart metering consequences; environmental targets and emissions markets; energy innovation and human capital accumulation; electric vehicles dissemination and their consequences on emission displacement, fuel costs, taxes revenues, transport sectors, electricity storage response, and so on.

Work has being done to evaluate the electricity demand response program using the H-GEMED model; compare the BU, TD, GEMED and H-GEMED model results to provide insights about the most recommended instruments to be used at each situation and the existent trade-offs of each of them; include the evaluation of diffuse CO2 atmospheric emissions, energy taxes and renewables promotion measures on the green tax reform assessment; and update the dataset used for this thesis' policy evaluations to provide actual and relevant policy recommendations.

Annex I The Computable General Equilibrium Model

This section describes the formulation of a CGE model. This model serves as the departure point for the development of the more complex policy assessment tools created for this thesis.

In order to clarify the explanation, we introduce firstly the formulation of a simple single country static Walrasian CGE model (section AI.1). This model represents a closed economy (i.e., without imports or exports), with two productive sectors (electricity and others), two productive factors (Labor and Capital) and one demand institution (the households).

Afterwards, on section AI.2, the simplest CGE model is extended to include a more realistic open economy model that includes government, investment and foreign relations. This second version includes the theoretical background needed to understand the models developed further on this thesis.

AI.1 A simple computable general equilibrium model

Assume an economy composed by two productive sectors (s, electricity and other producers); two products (g, electricity and other products); and one representative consumer (households) that receives payments by offering its labor force (labor) and lending money (capital) to the producers. Assuming the absence of any additional agent, Figure 8 represents the market and agents' relationships of this economy.

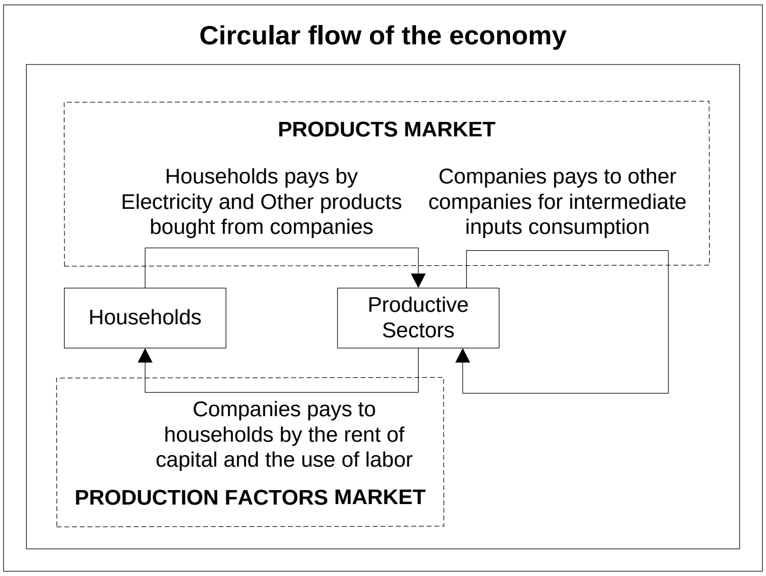

Figure 8. Circular flow of a closed economy without government.

The households demand the goods produced in the economy (electricity and other products) paying to the productive sectors according their respective prices. In turn, the households acquire their income from selling their work force and renting their owned capital to the industries.

Looking from the productive sectors perspective, the firms demand intermediate inputs from other productive sectors (electricity and other products), and additionally demand money (capital) and labor from households in order to produce their goods. Their income comes entirely from selling their products to the households.

If we are able to define a set of equations that define the agents' production and consumption decisions and, at the same time, if we assume that they interact in the economy markets in order to reach an agreement on the transactions levels and prices, it could be possible to determine an optimal equilibrium point where both producers and consumers are satisfied by their transaction decisions.

In the case of a closed economic system, where all products transacted in the economy have their sources and destinations established exhaustively, the set of equations obtained by the agents' behavior and from the markets equilibrium represents a Computable General Equilibrium (CGE) model.

In order to develop our simple CGE model, the following two sections define the partial optimization problem faced by each one of the economic agents (households and productive sectors). After that, we introduce the market clearing conditions necessary to achieve the economic equilibrium.

AI.1.1 The households partial equilibrium problem

There is only one representative household in our simplified economy. Its objective is to choose its consumption bundle with the intention of maximizing its welfare subject to a budget constraint. Therefore, in general terms its problem can be stated as:

$$\text{Max:} \quad [\text{Wellfare}] \qquad \text{AI-1}$$

$$\text{Subject to:} \quad \begin{array}{l}[\text{budget constraint}] \\ \qquad \rightarrow [\text{expenditures} \leq \text{Available Income}]\end{array} \qquad \text{AI-2}$$

The welfare function can be represented by a utility function in the shape of an Extended Linear Expenditure System ($\mathrm{U}\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{H}}\right) = \sum_{\mathrm{g}} \bar{\mathrm{c}}_{\mathrm{g}}^{\mathrm{H}} \ln\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{H}}\right)$, where $\sum_{\mathrm{g}} \bar{\mathrm{c}}_{\mathrm{g}}^{\mathrm{H}} = 1$). Meanwhile, the total expenditure of households corresponds to the sum of expenses in buying products ($\sum_{\mathrm{g}} \mathrm{P}_{\mathrm{g}} \mathrm{Q}_{\mathrm{g}}^{\mathrm{H}}$) while their income is acquired from the ownership of labor and capital ($\sum_{\mathrm{pf}} \mathrm{P}_{\mathrm{pf}} \bar{\mathrm{q}}_{\mathrm{pf}}^{\mathrm{H}}$).

Accordingly, the household consumption decision could be expressed as the following optimization problem:

$$\underset{\mathrm{Q}_{\mathrm{g}}^{\mathrm{H}}}{\text{Max:}} \qquad U\left(\mathrm{Q}_{1}^{\mathrm{H}}, \dots, \mathrm{Q}_{\mathrm{g}}^{\mathrm{H}}\right) = \sum_{\mathrm{g}=elect,others} \bar{\mathrm{c}}_{\mathrm{g}}^{\mathrm{H}} ln\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{H}}\right) \qquad \text{AI-3}$$

$$\text{Subject to:} \qquad \sum_{g=elect,others} P_{\mathrm{g}} \mathrm{Q}_{\mathrm{g}}^{\mathrm{H}} \leq \sum_{pf=\text{Labor and Capital}} P_{\mathrm{pf}} \bar{\mathrm{q}}_{\mathrm{pf}}^{\mathrm{H}} \qquad \text{AI-4}$$

, where $\bar{\mathrm{c}}_{\mathrm{g}}^{\mathrm{H}}$ is the marginal consumption propensity for each good g; P_{g} is the price of good g perceived by the households; $\mathrm{Q}_{\mathrm{g}}^{\mathrm{H}}$ is the quantity demanded by households of product g; $\bar{\mathrm{q}}_{\mathrm{pf}}^{\mathrm{H}}$ is the production factor pf (Labor or Capital) initial endowment owned by the households.

The further assemblies of the general equilibrium and the hybrid model proposed by this work follow a mixed complementarity formulation. Therefore, we introduce bellow the equivalent household optimization decision described by its Lagrangean and Karush-Kuhn-Tucker (KKT) conditions. The equivalent optimization problem can be defined as:

$$\underset{\mathrm{Q}_{\mathrm{g}}^{\mathrm{H}}}{\text{Max:}} \qquad \mathcal{L}\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{H}}, \lambda^{\mathrm{H}}\right) = \left[\sum_{\mathrm{g}} \bar{\mathrm{c}}_{\mathrm{g}}^{\mathrm{H}} ln\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{H}}\right)\right] - \lambda^{\mathrm{H}} \left[\sum_{\mathrm{g}} P_{\mathrm{g}} \mathrm{Q}_{\mathrm{g}}^{\mathrm{H}} - \sum_{pf} P_{\mathrm{pf}} \bar{\mathrm{q}}_{\mathrm{pf}}^{\mathrm{H}}\right] \qquad \text{AI-5}$$

, and the respective KKT conditions provide the following optimality conditions:

Stationary conditions:

$$\frac{\partial \mathcal{L}\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{H}}, \lambda^{\mathrm{H}}\right)}{\partial \mathrm{Q}_{\mathrm{g}}^{\mathrm{H}}} = -\frac{\bar{\mathrm{c}}_{\mathrm{g}}^{\mathrm{H}}}{\mathrm{Q}_{\mathrm{g}}^{\mathrm{H}}} + \lambda^{\mathrm{H}} P_{\mathrm{g}} = 0 \qquad \text{AI-6}$$

Feasibility and complementarity conditions to inequality constraints:

$$\left(\sum_{g} P_{g} Q_{g}^{H}\right) - \sum_{pf} P_{pf} \bar{q}_{pf}^{H} \leq 0 \quad \perp \quad \lambda^{H} \geq 0 \qquad \text{AI-7}$$

Assuming local non-satiability for the household budget constraint, i.e., the household expends all its income in goods purchase, and adding the conditions from equation AI-6 and $\sum_{g} \bar{c}_{g}^{H} = 1$, it is possible to obtain the household demand equation (equation AI-8). The partial equilibrium household problem of maximizing its utility can therefore be described by the following demand equation:

Parameters: $\bar{c}_{g}^{H}$, P_{g}, P_{pf}, $\bar{q}_{pf}^{H}$

Variables: Q_{g}^{H}

Equations:

$$Q_{g}^{H} = \frac{\bar{c}_{g}^{H} \sum_{pf} P_{pf} \bar{q}_{pf}^{H}}{P_{g}} \qquad \text{AI-8}$$

AI.1.2 The productive sectors partial equilibrium problem

The productive sector central objective is to maximize its profits. Its objective is constrained by technological limitations, which determine the feasible combinations of intermediate inputs and production factors necessary to produce goods.

Max:

$$[\text{Profit}] = \begin{bmatrix} \text{Firm} \\ \text{Income} \end{bmatrix} - \begin{bmatrix} \text{Firm} \\ \text{Costs} \end{bmatrix} \qquad \text{AI-9}$$

Subject to:

$$[\text{technological constraints}] \qquad \text{AI-10}$$

Considering first the decision to use production factors in the productive process, it is usual in economic theory to allow a certain substitution between the capital and labor in the production decision. For example, one particular sector as the agriculture could produce the same amount of food under a largely mechanized farming system or by intensive use of labor. In order to allow the substitution between using more equipment (capital) or more work force (labor) the technological constraint is described by the use of a statistical production function, like the one in equation AI-12, and the respective producer decision can be represented as the following optimization problem:

$$\underset{\mathrm{Q_{pf,s}}}{\text{Max:}} \quad \mathrm{P_s^{VA} Q_s^{VA}} - \sum_{pf} \mathrm{P_{pf} Q_{pf,s}} \qquad \text{AI-11}$$

$$\text{s.t.:} \quad \mathrm{CES}(\mathrm{Q_{pf,s}}) = \mathrm{Q}_{\mathrm{s}}^{VA} = \bar{\alpha}_{\mathrm{s}}^{VA}\left(\bar{a}_{\mathrm{s}}^{VA\_\mathrm{L}} L_s^{\frac{\bar{\sigma}_s^{VA}-1}{\bar{\sigma}_s^{VA}}} + \left(1-\bar{a}_{\mathrm{s}}^{VA\_L}\right) K_s^{\frac{\bar{\sigma}_s^{VA}-1}{\bar{\sigma}_s^{VA}}}\right)^{\frac{\bar{\sigma}_{\mathrm{s}}^{VA}}{\bar{\sigma}_{\mathrm{s}}^{VA}-1}} \qquad \text{AI-12}$$

, where $\mathrm{Q_s^{VA}}$ is the equivalent value-added composite product produced by combining labor and capital inputs by the sector s, $\mathrm{P_s^{VA}}$ is the price of the value-added composite; $\mathrm{Q_{pf,s}}(= \mathrm{L_s}\text{or } \mathrm{K_s})$ is the demanded quantity of labor or capital by the sector s; and $\mathrm{P_{pf}}$ is the production factor price (economy wage or capital rent price).

Equation AI-12 represents the technological constraints by means of a constant elasticity of substitution production function ($CES(\mathrm{Q_{pf,s}})$) which describe the feasible combinations proportions of labor and capital inputs, which can be used in the production of $\mathrm{Q}_{\mathrm{s}}^{VA}$, with a corresponding elasticity of substitution equal to $\bar{\sigma}_{\mathrm{s}}^{\mathrm{VA}}$.

The corresponding Lagrangean problem would be:

$$\underset{\mathrm{Q_{pf,s}}}{\text{Max:}} \quad \mathcal{L}_s(\mathrm{Q_{pf,s}}, \lambda_{\mathrm{s}}^{\mathrm{VA}}) = \mathrm{P_s^{VA} Q_s^{VA}} - \sum_{pf} \mathrm{P_{pf} Q_{pf,s}} + \lambda_{\mathrm{s}}^{\mathrm{VA}}[\mathrm{CES}(\mathrm{Q_{pf,s}}) - \mathrm{Q}_{\mathrm{s}}^{VA}] \qquad \text{AI-13}$$

, and the respective KKT conditions provide the following optimality conditions:

Stationary conditions:

$$\frac{\partial \mathcal{L}_s(\mathrm{Q_{pf,s}}, \lambda_{\mathrm{s}}^{\mathrm{VA}})}{\partial \mathrm{Q_{pf,s}}} = \mathrm{P_{pf}} - \lambda_{\mathrm{s}}^{\mathrm{VA}} \frac{\partial \mathrm{CES}(\mathrm{Q_{pf,s}})}{\partial \mathrm{Q_{pf,s}}} = 0 \qquad \text{AI-14}$$

Feasibility to equality constraints:

$$\frac{\partial \mathcal{L}_s(\mathrm{Q_{pf,s}}, \lambda_{\mathrm{s}}^{\mathrm{VA}})}{\partial \lambda_{\mathrm{s}}} = \mathrm{CES}(\mathrm{Q_{pf,s}}) - \mathrm{Q_s^{VA}} = 0 \quad \perp \quad \lambda_{\mathrm{s}} \qquad \text{AI-15}$$

Assuming that the value added aggregation has zero extraordinary profits (equation AI-18), and obtaining the transformation function between factors (Labor and Capital) from equation AI-14, the partial equilibrium productive sector problem of maximizing its profits could be described by:

Parameters: $\bar{\sigma}_{\mathrm{s}}^{VA}$, $\bar{\alpha}_j^{VA}$, $\bar{a}_j^{VA\_L}$, $\mathrm{P_{pf}}$, $\mathrm{Q_s^{VA}}$

Variables: $\mathrm{Q}_{\mathrm{pf,s}}$, $\mathrm{P}_{\mathrm{s}}^{\mathrm{VA}}$

Equations:

$$\begin{aligned}\left(\mathrm{Q}_{\mathrm{pf=Labor,s}}\right)^{\frac{1}{\bar{\sigma}_{\mathrm{s}}^{VA}}}\left(1-\bar{a}_{\mathrm{s}}^{VA_{\mathrm{L}}}\right)\left(\mathrm{P}_{\mathrm{pf=labor}}\right) \\ =\left(\mathrm{Q}_{\mathrm{pf=Capital}}\right)^{\frac{1}{\bar{\sigma}_{\mathrm{s}}^{VA}}}\left(\bar{a}_{\mathrm{s}}^{VA\_\mathrm{L}}\right)\left(\mathrm{P}_{\mathrm{pf=Capital}}\right)\end{aligned} \tag{AI-16}$$

$$\frac{\partial\mathcal{L}_s\left(\mathrm{Q}_{\mathrm{s}}^{\mathrm{VA}},\mathrm{Q}_{\mathrm{pf,s}},\lambda_{\mathrm{s}}\right)}{\partial\lambda_{\mathrm{s}}}=\mathrm{CES}\left(\mathrm{Q}_{\mathrm{pf,s}}\right)-\mathrm{Q}_{\mathrm{s}}^{\mathrm{VA}}=0 \quad \perp \quad \mathrm{p}_{\mathrm{s}}^{\mathrm{VA}} \tag{AI-17}$$

$$\mathrm{P}_{\mathrm{s}}^{\mathrm{VA}}\mathrm{Q}_{\mathrm{s}}^{\mathrm{VA}}=\sum_{pf}\mathrm{P}_{\mathrm{pf}}\mathrm{Q}_{\mathrm{pf,s}} \tag{AI-18}$$

AI.1.2.1. Adding the intermediate inputs demand to the production sector decision:

The previous producer optimization decision took only into account the production factor inputs labor and capital used in the sector. However, it is common that firms make use of final goods produced by other sectors in their production process. Returning to the agriculture example, besides the use of labor and capital factors, the sector could also make use of commercialized fertilizers produced by other sectors which, in turn, make use of chemicals produced by others, and so on.

The introduction of such use of intermediate input goods in the production process is described under a simpler approach if compared to the capital-labor substitution in our model. We consider that each intermediate input and production factor is combined through a Leontief production function[58]. Consequently, the final production problem can be described as:

$$\underset{\mathrm{Q}_{\mathrm{s}}^{\mathrm{VA}},\,Q_{g,s}^{II}}{Max:} \qquad \mathrm{P}_{\mathrm{s}}^{\mathrm{S}}\mathrm{Q}_{\mathrm{s}}^{\mathrm{S}}-\mathrm{P}_{\mathrm{s}}^{\mathrm{VA}}\mathrm{Q}_{\mathrm{s}}^{\mathrm{VA}}-\sum_{\mathrm{g}}\mathrm{P}_{\mathrm{g}}Q_{g,s}^{II} \tag{AI-19}$$

$$\text{Subject to:} \qquad \mathrm{Q}_{\mathrm{s}}^{\mathrm{S}}=min\left(\frac{\mathrm{Q}_{\mathrm{s}}^{\mathrm{VA}}}{\bar{c}_{\mathrm{s}}^{VA}},\frac{Q_{1,\mathrm{s}}^{II}}{\bar{c}_{1,s}^{II}},\ldots,\frac{\mathrm{Q}_{n,s}^{II}}{\bar{c}_{n,s}^{II}}\right) \tag{AI-20}$$

, where $\mathrm{Q}_{\mathrm{s}}^{\mathrm{S}}$ and $\mathrm{P}_{\mathrm{s}}^{\mathrm{S}}$ are the final quantity and price of the composite product sold to the market by sector s; $\mathrm{Q}_{\mathrm{s}}^{\mathrm{VA}}$ and $\mathrm{P}_{\mathrm{s}}^{\mathrm{VA}}$ are the equivalent value-added composite product and price obtained from the previous section optimization problem of

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[58] The Leontief type production function is: $Y=\min\left(x_i,x_j\right)=x_j$, if $x_j\geq x_i, j\neq i$.

combining the production factors labor and capital; and $Q_{g,s}^{II}$ is the quantity of intermediary input g utilized by a specific sector s.

As can be seen, this kind of production function is not differentiable and as a result the Lagrangean fist order condition is incalculable. However, this property does not cause bigger problems. The Leontief production function implies that the production factors will be used in fixed proportions at the optimum, consequently, the demand for each input will assume the shape described in equation AI-21.

$$\mathrm{Q_s^S} = \frac{\mathrm{Q_s^{VA}}}{\bar{c}_{\mathrm{s}}^{VA}} = \frac{Q_{1,\mathrm{s}}^{II}}{\bar{c}_{1,s}^{II}} = \cdots = \frac{\mathrm{Q}_{n,s}^{II}}{\bar{c}_{n,s}^{II}} \qquad \text{AI-21}$$

In addition, we assume that the activity within the sector presents a high degree of competitiveness causing the firms to act like price takers and present non-positive economic profits (equation AI-22):

Zero profit condition:

$$\mathrm{P_s^S Q_s^S} - \mathrm{P_s^{VA} Q_s^{VA}} - \sum_{\mathrm{g}} \mathrm{P_g} Q_{g,s}^{II} \leq 0 \qquad \text{AI-22}$$

Consequently, the partial equilibrium intermediate input productive sector problem of maximizing its profits could be described as:

Parameters: $\bar{c}_{\mathrm{s}}^{VA}$, $\bar{c}_{\mathrm{g,s}}^{II}$, $\mathrm{P_s^S}$, $\mathrm{P_s^{VA}}$

Variables: $Q_{g,s}^{II}$, $\mathrm{Q_s^{VA}}$, $\mathrm{Q_s^S}$

Equations:

$$\mathrm{Q_s^S} = \frac{Q_{g,s}^{II}}{\bar{c}_{g,s}^{II}} \quad \perp \quad Q_{g,s}^{II} \qquad \text{AI-23}$$

$$\mathrm{Q_s^S} = \frac{\mathrm{Q_s^{VA}}}{\bar{c}_{\mathrm{s}}^{VA}} \quad \perp \quad \mathrm{Q_s^{VA}} \qquad \text{AI-24}$$

$$\mathrm{P_s^S Q_s^S} - \mathrm{P_s^{VA} Q_s^{VA}} - \sum_{\mathrm{g}} \mathrm{P_g} Q_{g,s}^{II} \leq 0 \quad \perp \quad \mathrm{Q_s^S} \geq 0 \qquad \text{AI-25}$$

AI.1.3 The general equilibrium model: Market clearing conditions

Once defined both agents partial equilibrium decision problems, it remains to determine how they actually engage in their interaction in order to construct the general equilibrium model.

Integrate both agents decision (consumers and producers) requires the determination of the actual market where they confront their preferences in order to settle the selling and buying prices and quantities, and consequently achieve a market equilibrium. In our simple model there are two well defined markets where this occurs: the production factors market and the products market.

The market clearing condition of the production factors market states that the demand amount of factors by productive factors should be lesser or equal than the supplied quantity offered by the households, therefore:

$$\sum_{s} \mathrm{Q}_{\mathrm{pf},s} \leq \bar{\mathrm{q}}^{\mathrm{H}}_{\mathrm{pf}} \quad \perp \quad P_{\mathrm{pf}} \tag{AI-26}$$

At the product market situation, the sum of all demanded products should be lesser or equal to the sum of all produced goods, therefore:

$$\mathrm{Q}^{\mathrm{H}}_{\mathrm{g}} + \sum_{s} Q^{II}_{g,s} \leq \mathrm{Q}^{\mathrm{S}}_{\mathrm{s=g}} \quad \perp \quad \mathrm{P}^{\mathrm{S}}_{\mathrm{s=g}} \tag{AI-27}$$

Finally, if we consider together the households and productive sectors optimization problems, the activities zero-profit conditions and the market clearing conditions it is possible to assemble the set of equations that constitutes the CGE model.

AI.1.4 The closed economy CGE model

Considering simultaneously the households and productive sectors behavior in unison with the market clearing conditions it is possible to determine the equilibrium prices and quantities where all agents of the economy are satisfied.

The variables to our simplified model can therefore be represented by:

	Household problem:
$\mathrm{Q}^{\mathrm{H}}_{\mathrm{g}}$	Household goods demand
$\mathrm{P}^{\mathrm{S}}_{\mathrm{s=g}}$	Selling price of the commodity g
P_{pf}	Price of production factor pf

	Productive sectors problem:
$\mathrm{Q_{pf,s}}$	Quantity of production factor pf utilized in a specific sector s
$\mathrm{Q_s^{VA}}$	Quantity of value added composite good produced by sector s
$\mathrm{P_s^{VA}}$	Price of value added composite good of a specific sector s
$Q_{g,s}^{II}$	Quantity of intermediary input g utilized by a specific sector s
$\mathrm{Q_s^S}$	Quantity of the commodity produced by a specific sector s

, while the equations are listed below:

Type	Model Equations	
Household behavior	$Q_g^H = \frac{\bar{c}_g^H \sum_{pf} P_{pf} \bar{q}_{pf}^H}{P_g} \quad ,\forall g$	AI-8
Production sector behavior	$\begin{aligned}&\left(Q_{pf=Labor,s}\right)^{\bar{\sigma}_s^{VA}} \left(\bar{a}_s^{VA\_L}\right)\left(P_{pf=Capital}\right) \\ &\quad = \left(Q_{pf=Capital}\right)^{\bar{\sigma}_s^{VA}} \left(1-\bar{a}_s^{VA_L}\right)\left(P_{pf=labor}\right) \quad ,\forall s\end{aligned}$	AI-16
	$CES\left(Q_{pf,s}\right) - Q_s^{VA} = 0 \quad \perp \quad p_s^{VA} \quad ,\forall s$	AI-17
	$\mathrm{P_s^{VA} Q_s^{VA} = \sum_{pf} P_{pf} Q_{pf,s}} \quad ,\forall \mathrm{s}$	AI-18
	$Q_s^S = \frac{Q_{g,s}^{II}}{\bar{c}_{g,s}^{II}} \quad \perp \quad Q_{g,s}^{II} \quad ,\forall g,s$	AI-23
	$Q_s^S = \frac{Q_s^{VA}}{\bar{c}_s^{VA}} \quad \perp \quad Q_s^{VA} \quad ,\forall s$	AI-24
	$P_s^S Q_s^S - P_s^{VA} Q_s^{VA} - \sum_g P_g Q_{g,s}^{II} \leq 0 \quad \perp \quad Q_s^S \geq 0 \quad ,\forall s$	AI-25
Market clearing conditions	$\mathrm{\sum_s Q_{pf,s} \leq \bar{q}_{pf}^H} \quad \perp \quad \mathrm{P_{pf}} \quad ,\forall \mathrm{pf}$	AI-26
	$\mathrm{Q_g^H + \sum_s Q_{g,s}^{II} \leq Q_{s=g}^S} \quad \perp \quad \mathrm{P_{s=g}^S} \quad ,\forall \mathrm{s = g}$	AI-27

, where $\mathrm{CES\left(Q_{pf,s}\right) = Q_s^{VA} = \bar{\alpha}_s^{VA} \left(\sum_{pf} \bar{a}_{pf,s}^{VA} Q_{pf,s}^{\frac{\bar{\sigma}_s^{VA}-1}{\bar{\sigma}_s^{VA}}}\right)^{\frac{\bar{\sigma}_s^{VA}}{\bar{\sigma}_s^{VA}-1}}}$.

As can be seen, the model sustains five endogenous variables in $\mathbb{R}^{g\,(=s)}$, one in $\mathbb{R}^{pf}$ (=$\mathbb{R}^{2}$), one in $\mathbb{R}^{pfxs}$ (=$\mathbb{R}^{2xs}$), and one in $\mathbb{R}^{gxs}$. At the same time, our CGE model is composed by seven equations of g (=s) dimensions, one of pf (=2) dimensions and one of gxs dimension.

Therefore, the CGE model represented is a square system of equations, with the same amount of endogenous variables and equations. Under an independent set of equations, the equilibrium value of all variables can be determined while all agents first order optimization conditions are respected. A solution to this system of equations is a general equilibrium solution to the economy described.

The equation system still presents a property known as Walras's Law[59], which holds that one equation is functionally dependent on the others and can be dropped. Therefore is common to assume a commodity price as a "numéraire", calculating all the other prices as relative prices in relation to this commodity's price. This thesis adopts a price index of all products transacted on the economy as the "numéraire" of the CGE model.

AI.1.5 Applying the model to an actual economy

In order to apply the developed CGE model to an actual economy, we still need to determine the value of each parameter described in the equation system. The model parameters are listed below:

---

[59] If n-1 markets are in equilibrium, necessarily the nth must be in equilibrium.

	Household Behavior:
$\bar{q}^{H}_{pf}$	Representative Household initial endowment of pf production factor
$\bar{c}^{H}_{g}$	Household marginal consumption propensity of a specific domestic good
	Productive sector parameters:
$\bar{\alpha}^{VA}_{s}$	Productivity parameter of sector value added composite good production function
$\bar{a}^{VA}_{s,pf}$	Share parameter of product factor on value added composite good production function
$\bar{\sigma}^{VA}_{s}$	Elasticity of substitution between productive factors of sector s
$\bar{c}^{II}_{g,s}$	Share parameter of intermediate composites inputs g on sector s production function
$\bar{c}^{VA}_{s}$	Share parameter of value added composite input on sector s production function

The substitution elasticity parameters of the production functions ($\bar{\sigma}^{VA}_{s}$) can be obtained from statistical estimations of historical labor-capital substitution inside each sector. All other parameters have to be calibrated with the national accounts for a certain year of the specific country studied.

AI.1.5.1. National accountability data

Worldwide, national statistical organizations commonly aggregate all country transactions information annually through the use of national accounts, input-output matrices and social accountability matrices.

At our simplified economy, a social accountability matrix could be described as in the example bellow:

Table 22. Social accountability matrix of an example country at a specific year.

			Uses				
			Productive Sectors		Productive Factors		Institutions
			electricity	others	Capital	Labor	Households
Resources	Products	electricity	5	10			20
		others	10	20			50
	Productive Factors	Capital	15	20			
		Labor	5	30			
	Institutions	Households			35	35	

Source: own elaboration.

The objective of such accounts is to aggregate all expenditures (columns) and incomes (rows) made by each acting economic agent in order to analyze the money flows in a region or a specific country economy.

An important attribute of such accounting system is that, as it represents all agents of the economy, the sum of all expenses should equal their respective income for all agents (each row sum should equal its corresponding column sum). This property is a strong signal of the compatibility between this accountability scheme and the formulation of closed general economic models such as CGE models.

In order to clarify the values contained in such matrix, take for example the electricity sector in Table 22. In order to produce electricity in the studied year, the electricity sector had to spend 5€ in its own electricity consumption, 10€ in other products (like fuel, equipments needed to repair installations,…), 15€ in capital (amortization costs of installations or new investments made) and 5€ in labor payments. The sum of expenses of the electricity sector production would be 35€.

On the other hand, if we analyze the electricity product row, we can conclude that the electricity was demanded by its own sector, by the other production sectors, and by the households in amounts of 5€, 10€ and 20€ respectively. As previously said, we can observe that in such accountability scheme the total income (sources) corresponds to the same amount of electricity expenses (destinations), totalizing 35€.

AI.1.5.2. The initial year calibration process

The accountability matrix presented before provides all the necessary information in order to determine the remaining undefined CGE parameters. In terms of CGE model variables and parameters, Table 22 could be rewritten as in the following:

Table 23. Social accountability to a specific year in our simplified economy.

			Uses				
			Productive Sectors		Productive Factors		Institutions
			electricity	others	Capital	Labor	Households
Resources	Products	electricity others	$\bar{p}_g^{S^{INITIAL}} \bar{q}_{g,s}^{II^{INITIAL}}$				$\bar{p}_g^{S^{INITIAL}} \bar{q}_g^{H}$
	Productive Factors	Capital Labor	$\bar{p}_{pf}^{INITIAL} \bar{q}_{pf,s}^{INITIAL}$				
	Institutions	Households			$\bar{p}_{pf}^{INITIAL} \bar{q}_{pf}^{H}$		

Source: own elaboration.

A CGE model is a relative prices model with the property of homogeneity of degree zero with respect to prices. Therefore, in order to calibrate the initial equilibrium quantities to the numbers observed on the national accountability matrix, we can set all initial prices to the unity at the initial equilibrium point with the only consequence of changing the units of the transacted goods quantity measurement.

Accordingly, the household initial endowments of production factors ($\overline{\mathrm{q}}_{\mathrm{pf}}^{\mathrm{H}}$) can be direct acquired from the table and, at the same time, all initial values of prices and quantities can be determined.

As our model should be able to reproduce the country transactions at the initial year, we can make use of the model equations, together with the parameters already defined in order to determine the remaining parameters ($\overline{\alpha}_{\mathrm{s}}^{\mathrm{VA}}$, $\overline{\mathrm{a}}_{\mathrm{s,pf}}^{\mathrm{VA}}$, $\bar{c}_{g,s}^{II}$, $\bar{c}_{s}^{VA}$, $\overline{\mathrm{c}}_{\mathrm{g}}^{\mathrm{H}}$):

$$\overline{\mathrm{a}}_{\mathrm{s,pf}}^{\mathrm{VA}} = \frac{\left(\overline{\mathrm{P}}_{\mathrm{pf}}{}^{\mathrm{INITIAL}}\overline{\mathrm{Q}}_{\mathrm{pf,s}}{}^{\mathrm{INITIAL}}\right)^{\frac{1}{\overline{\sigma}_{\mathrm{s}}^{\mathrm{VA}}}}}{\sum_{\mathrm{pf}}\overline{\mathrm{P}}_{\mathrm{pf}}{}^{\mathrm{INITIAL}}\left(\overline{\mathrm{Q}}_{\mathrm{pf,s}}{}^{\mathrm{INITIAL}}\right)^{\frac{1}{\overline{\sigma}_{\mathrm{s}}^{\mathrm{VA}}}}} \qquad \text{AI-28}$$

$$\overline{\alpha}_{\mathrm{s}}^{\mathrm{VA}} = \overline{\mathrm{Q}}_{\mathrm{s}}^{\mathrm{VA\,INITIAL}}\left(\sum_{\mathrm{pf}}\overline{\mathrm{a}}_{\mathrm{pf,s}}^{\mathrm{VA}}\overline{\mathrm{Q}}_{\mathrm{pf,s}}{}^{\mathrm{INITIAL}\frac{\overline{\sigma}_{\mathrm{s}}^{\mathrm{VA}}-1}{\overline{\sigma}_{\mathrm{s}}^{\mathrm{VA}}}}\right)^{-\frac{\overline{\sigma}_{\mathrm{j}}^{\mathrm{VA}}}{\overline{\sigma}_{\mathrm{j}}^{\mathrm{VA}}-1}} \qquad \text{AI-29}$$

$$\overline{\mathrm{c}}_{\mathrm{s}}^{\mathrm{VA}} = \frac{\mathrm{Q}_{\mathrm{s}}^{\mathrm{VA}}}{\overline{\mathrm{Q}}_{\mathrm{s}}^{\mathrm{S}}{}^{\mathrm{INITIAL}}} \qquad \text{AI-30}$$

$$\overline{\mathrm{c}}_{\mathrm{g,s}}^{\mathrm{II}} = \frac{\overline{\mathrm{Q}}_{\mathrm{g,s}}^{\mathrm{II}}{}^{\mathrm{INITIAL}}}{\overline{\mathrm{Q}}_{\mathrm{s}}^{\mathrm{S}}{}^{\mathrm{INITIAL}}} \qquad \text{AI-31}$$

$$\overline{\mathrm{c}}_{\mathrm{g}}^{\mathrm{H}} = \frac{\overline{\mathrm{Q}}_{\mathrm{g}}^{\mathrm{H}}{}^{\mathrm{INITIAL}}}{\sum_{\mathrm{g}}\overline{\mathrm{Q}}_{\mathrm{g}}^{\mathrm{H}}{}^{\mathrm{INITIAL}}} \qquad \text{AI-32}$$

AI.1.6 Evaluating a policy simulation

Many policy evaluations can be implemented even under the simple general equilibrium model proposed in this section. One could for example evaluate the effects to the country economy of the introduction (or an increase) of an electricity production tax.

An electricity tax would correspond to a difference between the actual production selling price faced by producers and the buying price perceived by the households. Therefore, such tax instrument could be easily represented by adding an equation that relates both demand and supply prices for the case of the electricity products taking into account the tax burden, like the following one

$$\mathrm{P}_{\mathrm{s=elec}} = (1+\mathrm{tx})\mathrm{P}^{\mathrm{S}}_{\mathrm{s=elec}} \qquad \text{AI-33}$$

, where $\mathrm{P}_{\mathrm{s=elec}}$ is the electricity price perceived by the households, $\mathrm{P}^{\mathrm{S}}_{\mathrm{s=elec}}$ is the production price without taxes, and tx is the new level of the tax aliquot of electricity.

However, the inclusion of such equation is not the only modification required to evaluate such policy. It is still necessary to determine the destination of the new acquired tax income. As was already said, the general equilibrium model is a closed economic system, where all origins and destinations of the money flows of the economy should be entirely expressed. In the case of neglecting to include any money flow in the model, a certain amount of money wouldn’t present a determined destination. This lack of destination would cause a leakage of funds in the economy flows (in this case the leakage would correspond to the electricity tax income) which in turn would avoid achieving a relevant equilibrium solution to the equation´s system.

In order to avoid such problem in our example, we consider that the income from the electricity taxes is completely redirected to households as direct transfers. Consequently, the household budget constraint equation (equation AI-4) should be modified to include the new revenue source:

$$\left(\sum_{\mathrm{s}} P_{\mathrm{s}}\mathrm{Q}^{\mathrm{H}}_{\mathrm{s}}\right) - \sum_{pf} P_{\mathrm{pf}}\bar{\mathrm{q}}^{\mathrm{H}}_{\mathrm{pf}} - \mathrm{tx}\,\mathrm{P}^{\mathrm{S}}_{\mathrm{s}}\,\mathrm{Q}^{\mathrm{S}}_{\mathrm{s}} \leq 0 \quad , \qquad s = electricity \qquad \text{AI-34}$$

Finally, it is possible to execute the simulation in order to evaluate the changes of such tax policy. At an initial situation without the presence of any electricity tax, the tx term should be equal to zero, and the initial equilibrium should reflect exactly the national accountability matrix presented in Table 22.

The counterfactual simulation would include an electricity tax value different of zero. The CGE solution under this new tax policy would provide the ex-post effects on prices and quantities of the tax introduction on the economy.

An important point to underline is that the new equilibrium results obtained would take into account not only the direct effects of the increase in prices promoted by the tax introduction but also the indirect, income and rebound effects on demanded quantities, labor and capital prices and other sectors production levels originated from the new tax policy. The evaluation of these indirect effects, if present at significant amounts, points to the main advantages of adopting a general equilibrium approach when compared to a sector/demand specific partial equilibrium policy assessment.

AI.2 The Top-down model - An open economy CGE static model: including government, investment and foreign relations

Until now, the CGE model described in this section represented a closed economy with the presence of only one acting institution (the households). The following sections will introduce further extensions including international relationships and one additional institution (the government) to the CGE model. Additionally, the investment decisions in the economy by means of capital goods demand and the presence of indirect taxes will also be introduced to the model.

AI.2.1 The extended CGE model: economy structure

The extended version of the CGE model increases the number of relationships between agents represented in the economy. The circular flow of the economy, presented at Figure 8 needs to be updated to represent the newly added economic agents:

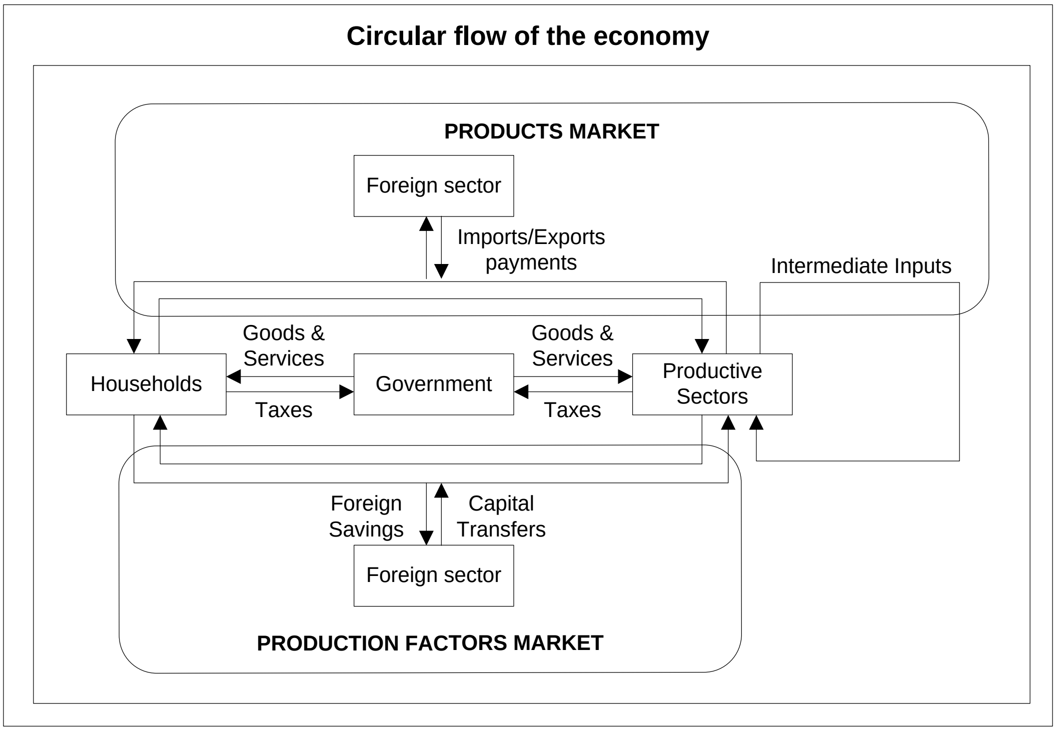

Figure 9. Circular flow of economy.

The extended CGE model presented in this section is still of static neoclassic formulation, however it now includes the relations of a country (Spain) with outer regions (foreign sector); the presence of two production factors (capital and labor); two institutions (government and representative household); s productive sectors; g transacted goods; and taxes under social contributions, production sectors and final products.

In order to clarify the main relations between the goods production and consumption in the model we could summarize the flow of goods in the economy as in the diagram bellow:

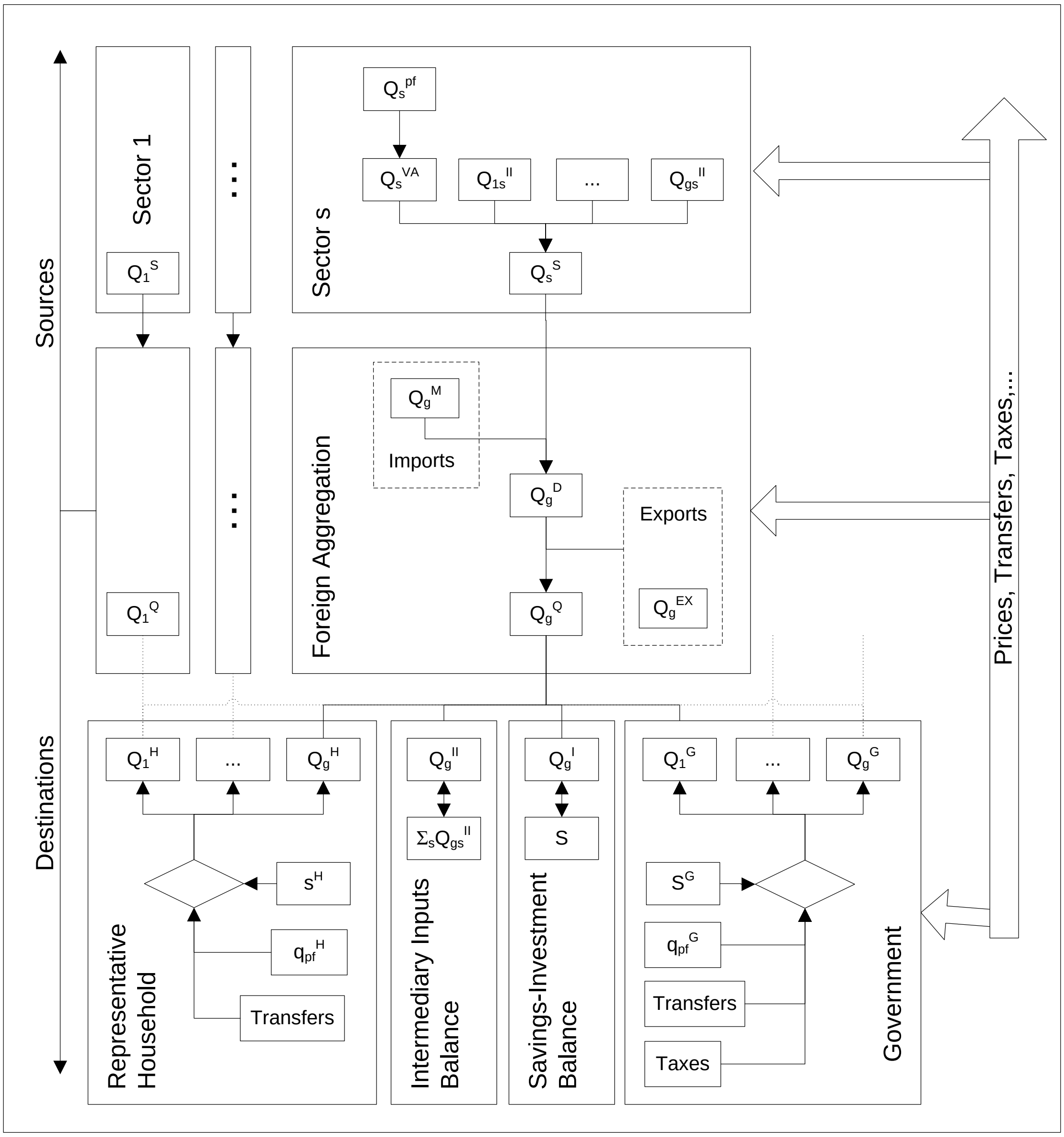

Figure 10. Goods sources and destinations on the economy. Nested structure of production, international and demand aggregations.

The upper part of the diagram (Figure 10) represents the goods supply sources, meanwhile the bottom part describes the destinations of the products transacted in our economy. The goods are supplied either by the domestic production or by imports. The possible destinations of these goods are represented by the goods demanded by the exterior (exports) and the goods demanded inside the national territory by the households, government, intermediate productive inputs consumption and the investment goods demand.

The production decision of each sector represented by the top-level rectangle of the diagram is modeled through the use of CES and Leontief production functions, like in the previous section. The domestically produced good ($Q^{S}_{s=g}$) is then combined with imported goods (Q^{M}_{g}) in order to produce an equivalent composite good (Q^{D}_{g}) through an Armington aggregation assumption (represented at the center in the figure by the foreign aggregation rectangle).

The total supplied composite good (Q^{D}_{g}) is confronted with the external and internal demand for goods. Primarily, the amount of goods aimed to exports (Q^{EX}_{g}) and the amount heading for the national internal market (Q^{Q}_{g}) are divided through the use of a constant elasticity of transformation function (CET). Finally, the remaining internal goods supply faces the national agents' consumption decision represented by institutions demand (government, Q^{G}_{g}, and household, Q^{H}_{g}), sectors intermediate input demand ($Q^{II}_{s,g}$) and investment goods demand (Q^{I}_{g}) as schematized in the bottom-level rectangles in

Figure 10.

As already stated in the previous section, the households and the productive sectors behaviors were represented by partial equilibrium problems, described in sections AI.1.1 and AI.1.2 respectively. This chapter is responsible to determine the additional and necessary behavioral rules and functional forms for the international aggregations (section AI.2.2), the government (section AI.2.3), the investment decisions (section AI.2.4), and the market clearing conditions (section AI.2.5) in order to achieve the economy equilibrium. A pure CGE model incorporating all these elements is described at section AI.2.6.

AI.2.2 International trade

The way chosen to include foreign goods trade to the model is to assume that goods are differentiated according to their origins (Spain and the Rest of the World). This allows for the possibility of intra-industry trade despite the assumption of exogenous world prices (i.e., the small country assumption, namely that Spain is price taker in international markets). The international trade in electricity for the Spanish economy represents a very small share in all the international flows, so those assumptions play a minor role in the aimed policy simulation quantitative results.

Firstly, the domestically produced goods are summed up to the imports in order to compose the total domestic supply. The resulting total supply is then divided between the goods demanded by the exterior and the goods demanded by the domestic market.

The total goods supplied in the economy is represented in the model by a composite good ($\mathrm{Q_g^D}$) created by means of an Armington aggregation scheme. The main purpose of this aggregation is to avoid the specialization in either a domestic-only or an imported-only source for the goods, which is unreal at real world circumstances. The basic optimization problem is to determine the optimal mix between domestic produced goods ($\mathrm{Q_{s=g}^S}$) and imported goods ($\mathrm{Q_g^M}$), assuming an imperfect substitution between these goods (by the use of a CES aggregation structure) meanwhile the combined costs of the different good sources are minimized. The Armington aggregation can therefore be expressed as the following optimization problem:

$$\underset{\mathrm{Q_g^S,Q_g^M}}{\text{Max:}} \qquad \mathrm{P_g^D Q_g^D - P_g^S Q_g^S - \bar{p}_g^M Q_g^M} \qquad \text{AI-35}$$

$$\text{s.t.:} \qquad \mathrm{Q_g^D} = \mathrm{CES}\left(\mathrm{Q_g^S, Q_g^M}\right) = \bar{\alpha}_g^D \left(\bar{\mathrm{a}}_g^D \mathrm{Q_g^S}^{\frac{\bar{\sigma}_g^D - 1}{\bar{\sigma}_g^D}} + \left(1 - \bar{\mathrm{a}}_g^D\right) \mathrm{Q_g^M}^{\frac{\bar{\sigma}_g^D - 1}{\bar{\sigma}_g^D}} \right)^{\frac{\bar{\sigma}_g^D}{\bar{\sigma}_g^D - 1}} \qquad \text{AI-36}$$

, with the correspondent lagrangean problem:

$$\underset{\mathrm{Q_g^S,Q_g^M}}{\text{Max:}} \qquad \mathcal{L}_\mathrm{g}\left(\mathrm{Q_g^D, Q_g^M, \lambda_g^D}\right) = \mathrm{P_g^D Q_g^D - P_g^S Q_g^S - \bar{p}_g^M Q_g^M + \lambda_g^D\left[CES\left(Q_g^S, Q_g^M\right) - Q_g^D\right]} \qquad \text{AI-37}$$

, and the respective KKT optimality conditions:

Stationary conditions:

$$\frac{\mathcal{L}_\mathrm{g}\left(\mathrm{Q_g^D, Q_g^M, \lambda_g^D}\right)}{\partial \mathrm{Q_g^S}} = \mathrm{P_g^S} - \lambda_\mathrm{g}^\mathrm{D} \frac{\partial \mathrm{CES}\left(\mathrm{Q_g^S, Q_g^M}\right)}{\partial \mathrm{Q_g^S}} = 0 \qquad \text{AI-38}$$

$$\frac{\mathcal{L}_\mathrm{g}\left(\mathrm{Q_g^D, Q_g^M, \lambda_g^D}\right)}{\partial \mathrm{Q_g^M}} = \mathrm{\bar{p}_g^M} - \lambda_\mathrm{g}^\mathrm{D} \frac{\partial \mathrm{CES}\left(\mathrm{Q_g^S, Q_g^M}\right)}{\partial \mathrm{Q_g^M}} = 0 \qquad \text{AI-39}$$

Feasibility to equality constraints:

$$\frac{\mathcal{L}_{\mathrm{g}}\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{D}},\mathrm{Q}_{\mathrm{g}}^{\mathrm{M}},\lambda_{\mathrm{g}}^{\mathrm{D}}\right)}{\partial\lambda_{\mathrm{g}}^{\mathrm{D}}} = \mathrm{Q}_{\mathrm{g}}^{\mathrm{D}} - \mathrm{CES}\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{S}},\mathrm{Q}_{\mathrm{g}}^{\mathrm{M}}\right) = 0 \qquad \text{AI-40}$$

Similar to what happened in the productive sector problem (section AI.1.2.1), the maximization problem that describes the Armington aggregate obliges us to determine the existence or not of extraordinary profits in the imports activity. Once again we assume that the international trade presents non-positive economic profits, which could be explained by a high degree of competition in this kind of service. Therefore, the zero profit equation that reflects this assumption can be described as shown below:

Zero profit condition:

$$\mathrm{P}_{\mathrm{g}}^{\mathrm{D}}\mathrm{Q}_{\mathrm{g}}^{\mathrm{D}} - \mathrm{P}_{\mathrm{g}}^{\mathrm{S}}\mathrm{Q}_{\mathrm{g}}^{\mathrm{S}} - \bar{\mathrm{p}}_{\mathrm{g}}^{\mathrm{M}}\mathrm{Q}_{\mathrm{g}}^{\mathrm{M}} = 0 \qquad \text{AI-41}$$

Combining equations AI-38 and AI-39 it is possible to obtain the function that determines the proportion between $\mathrm{Q}_{\mathrm{g}}^{\mathrm{S}}$ and $\mathrm{Q}_{\mathrm{g}}^{\mathrm{M}}$. The partial equilibrium Armington import aggregation optimization problem could be described as:

Parameters: $\bar{\sigma}_{\mathrm{g}}^{D}, \bar{\alpha}_{g}^{D}, \bar{\mathrm{a}}_{\mathrm{g}}^{D}, \mathrm{Q}_{\mathrm{g}}^{\mathrm{D}}, \mathrm{Q}_{\mathrm{g}}^{\mathrm{S}}, \mathrm{P}_{\mathrm{g}}^{\mathrm{S}}, \bar{\mathrm{p}}_{\mathrm{g}}^{\mathrm{M}}$

Variables: $\mathrm{Q}_{\mathrm{g}}^{\mathrm{S}}, \mathrm{Q}_{\mathrm{g}}^{\mathrm{M}}, \mathrm{P}_{\mathrm{g}}^{\mathrm{D}}$

Equations:

$$\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{S}}\right)^{\frac{1}{\bar{\sigma}_{\mathrm{s}}^{VA}}}\left(1-\bar{\mathrm{a}}_{\mathrm{g}}^{D}\right)\left(\mathrm{P}_{\mathrm{g}}^{\mathrm{S}}\right) = \left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{M}}\right)^{\frac{1}{\bar{\sigma}_{\mathrm{s}}^{VA}}}\left(\bar{\mathrm{a}}_{\mathrm{g}}^{D}\right)\left(\bar{\mathrm{p}}_{\mathrm{g}}^{\mathrm{M}}\right) \qquad \text{AI-42}$$

$$\frac{\mathcal{L}_{\mathrm{g}}\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{D}},\mathrm{Q}_{\mathrm{g}}^{\mathrm{M}},\lambda_{\mathrm{g}}^{\mathrm{D}}\right)}{\partial\lambda_{\mathrm{g}}^{\mathrm{D}}} = \mathrm{Q}_{\mathrm{g}}^{\mathrm{D}} - \mathrm{CES}\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{S}},\mathrm{Q}_{\mathrm{g}}^{\mathrm{M}}\right) = 0 \qquad \text{AI-43}$$

$$\mathrm{P}_{\mathrm{g}}^{\mathrm{D}}\mathrm{Q}_{\mathrm{g}}^{\mathrm{D}} - \mathrm{P}_{\mathrm{g}}^{\mathrm{S}}\mathrm{Q}_{\mathrm{g}}^{\mathrm{S}} - \bar{\mathrm{p}}_{\mathrm{g}}^{\mathrm{M}}\mathrm{Q}_{\mathrm{g}}^{\mathrm{M}} = 0 \qquad \text{AI-44}$$

The second international trade component, the exports, is defined by the split of the total supplied good ($\mathrm{Q}_{\mathrm{g}}^{\mathrm{D}}$) between the domestic offer ($\mathrm{Q}_{\mathrm{g}}^{\mathrm{Q}}$) and the exports ($\mathrm{Q}_{\mathrm{g}}^{\mathrm{EX}}$). The main objective of this disaggregation is to maximize the surplus obtained from the income of the different destinations sales (domestic and export sales) minus the total costs of acquiring the composite good.

Once more, in order to avoid the specialization in selling goods only to the exterior or to the internal market, whichever presents the higher prices, we assume an imperfect substitutability between exports and domestic sales. This is done by introducing a constant elasticity transformation function (CET) in the disaggregation problem, which can be represented as:

$$\underset{\mathrm{Q_g^Q, Q_g^{EX}}}{\text{Max:}} \qquad \mathrm{P_g^Q Q_g^Q + \bar{p}_g^{EX} Q_g^{EX} - P_g^D Q_g^D} \qquad \text{AI-45}$$

$$\text{s.t.:} \qquad \mathrm{Q_g^D = CET(Q_g^Q, Q_g^{EX})} = \bar{\beta}_g^Q \left(\bar{b}_g^Q \mathrm{Q_g^Q}^{\frac{\bar{\sigma}_g^Q+1}{\bar{\sigma}_g^Q}} + (1-\bar{b}_g^Q)\mathrm{Q_g^{EX}}^{\frac{\bar{\sigma}_g^Q+1}{\bar{\sigma}_g^Q}} \right)^{\frac{\bar{\sigma}_g^Q}{\bar{\sigma}_g^Q+1}} \qquad \text{AI-46}$$

The problem is equivalent to:

$$\text{Max:} \quad \mathcal{L}_g(\mathrm{Q_g^Q, Q_g^{EX}}, \lambda_g^Q) = \mathrm{P_g^Q Q_g^Q + \bar{p}_g^{EX} Q_g^{EX} - P_g^D Q_g^D} + \lambda_g^Q[\mathrm{Q_g^D - CET(Q_g^Q, Q_g^{EX})}] \qquad \text{AI-47}$$

, and the respective KKT conditions provide the following first order optimality conditions:

Stationary conditions:

$$\frac{\partial \mathcal{L}_g(\mathrm{Q_g^Q, Q_g^{EX}}, \lambda_g^Q)}{\partial \mathrm{Q_g^Q}} = \mathrm{P_g^Q} - \lambda_g^Q \frac{\partial \mathrm{CET(Q_g^Q, Q_g^{EX})}}{\partial \mathrm{Q_g^Q}} = 0 \qquad \text{AI-48}$$

$$\frac{\partial \mathcal{L}_g(\mathrm{Q_g^Q, Q_g^{EX}}, \lambda_g^Q)}{\partial \mathrm{Q_g^{EX}}} = \mathrm{\bar{p}_g^{EX}} - \lambda_g^Q \frac{\partial \mathrm{CET(Q_g^Q, Q_g^{EX})}}{\partial \mathrm{Q_g^{EX}}} = 0 \qquad \text{AI-49}$$

Feasibility to equality constraints:

$$\frac{\partial \mathcal{L}_g(\mathrm{Q_g^Q, Q_g^{EX}}, \lambda_g^Q)}{\partial \lambda_g^Q} = \mathrm{Q_g^D - CET(Q_g^Q, Q_g^{EX})} = 0 \qquad \text{AI-50}$$

Once more, we assume the zero profit condition (equation AI-53). Combining equations AI-48 and AI-49 it is possible to obtain the relation between $\mathrm{Q_g^Q}$ and $\mathrm{Q_g^{EX}}$ disaggregation (equation AI-51). Therefore, the goods supply disaggregation between domestic demand and exports can be represented as:

Parameters: $\bar{\sigma}_g^Q, \bar{\beta}_g^Q, \bar{b}_g^Q, \mathrm{\bar{p}}_g^{EX}, \mathrm{P_g^D}, \mathrm{Q_g^D}$

Variables: $\mathrm{Q_g^Q}, \mathrm{Q_g^{EX}}, \lambda_g^Q$

Equations:

$$\left(\left(\bar{b}_{\mathrm{g}}^{Q}\right)\bar{\mathrm{p}}_{\mathrm{g}}^{\mathrm{EX}}\right)^{\bar{\sigma}_{\mathrm{g}}^{Q}}\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{Q}}\right)=\left(\left(1-\bar{b}_{\mathrm{g}}^{Q}\right)\mathrm{P}_{\mathrm{g}}^{\mathrm{Q}}\right)^{\bar{\sigma}_{\mathrm{g}}^{Q}}\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{EX}}\right) \qquad \text{AI-51}$$

$$\frac{\partial\mathcal{L}_{g}\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{D}},\mathrm{Q}_{\mathrm{g}}^{\mathrm{Q}},\mathrm{Q}_{\mathrm{g}}^{\mathrm{EX}},\lambda_{\mathrm{g}}^{\mathrm{Q}}\right)}{\partial\lambda_{\mathrm{g}}^{\mathrm{Q}}}=\mathrm{Q}_{\mathrm{g}}^{\mathrm{D}}-\mathrm{CET}\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{Q}},\mathrm{Q}_{\mathrm{g}}^{\mathrm{EX}}\right)=0 \quad \perp \quad \lambda_{\mathrm{g}}^{\mathrm{Q}} \qquad \text{AI-52}$$

$$\mathrm{P}_{\mathrm{g}}^{\mathrm{Q}}\mathrm{Q}_{\mathrm{g}}^{\mathrm{Q}}+\bar{\mathrm{p}}_{\mathrm{g}}^{\mathrm{EX}}\mathrm{Q}_{\mathrm{g}}^{\mathrm{EX}}-\mathrm{P}_{\mathrm{g}}^{\mathrm{D}}\mathrm{Q}_{\mathrm{g}}^{\mathrm{D}}=0 \qquad \text{AI-53}$$

AI.2.3 The government

As said before, this model version model includes an additional institutional agent represented by the government. The role of the public sector is twofold: owner of resources (Y^{G}, e.g. from capital endowment, tax revenue and net foreign transfers), and purchaser of certain goods. Taxes consist of social contributions, value added taxes, other indirect taxes (production and product taxes), taxes on trade and direct taxes. The public sector also enters the model as a purchaser. The public sector expenditure (E^{G}) includes both market goods (i.e., output that is disposed of in the market at economically significant prices) and non-market goods (i.e., output that is provided at prices that are not economically significant).This consumption is in goods fixed proportions. The macroeconomic closure of the public sector is represented by and endogenous public savings level.

$$Y^{G}=\sum_{pf}P_{\mathrm{pf}}\bar{\mathrm{q}}_{\mathrm{pf}}^{\mathrm{G}}+\overline{transf}^{Ext-G}+Y^{TAX} \qquad \text{AI-54}$$

$$E^{G}=\sum_{g}\mathrm{P}_{\mathrm{g}}^{\mathrm{Q}}\bar{\mathrm{q}}_{\mathrm{g}}^{\mathrm{G}}+\overline{transf}^{G-H} \qquad \text{AI-55}$$

$$Y^{G}-E^{G}=S^{G} \qquad \text{AI-56}$$

$$Y^{TAX} \qquad \text{AI-57}$$

AI.2.4 Savings and Investments

The total savings in the economy (S) has as origin the level of savings from households (S^{H}), government (S^{G}) and foreign sectors ($\mathrm{S}^{\mathrm{Ext}}$):

$$\mathrm{S}=\mathrm{S}^{\mathrm{H}}+\mathrm{S}^{\mathrm{G}}+\mathrm{S}^{\mathrm{Ext}}=\mathrm{s}^{\mathrm{H}}\mathrm{Y}^{\mathrm{H}}+\mathrm{S}^{\mathrm{G}}+\mathrm{S}^{\mathrm{Ext}} \qquad \text{AI-58}$$

The only component of savings not expressed yet is the foreign saves. In terms of foreign currency, the difference between payments (from imports of goods and consumption of the representative household abroad) and receipts (export of goods, consumption of foreign tourists and net current and capital transfers from abroad) provides the necessity (capacity) of financial funding from abroad that the country faces, in other words, the net borrowing (lending) of the country from the exterior in the current year. This result corresponds to the balance of payments on this model and represents the foreign savings in the economy as expressed in the following equation:

$$\mathrm{S^{Ext}} = \sum_{\mathrm{g}} \mathrm{P_g^M Q_g^M} - \sum_{\mathrm{g}} \mathrm{P_g^{EX} Q_g^{EX}} - \overline{\mathrm{transf}}^{\mathrm{Ext-G}} - \overline{\mathrm{transf}}^{\mathrm{Ext\_K}} \qquad \text{AI-59}$$

Although, the model flow-of-funds is not yet entirely defined. The savings decision gives origin to an aggregated saving amount that requires investment counterparty. Therefore, it is necessary to determine the assumptions concerning the investment decisions. In a static model, as this one, these assumptions will then determine the destination of the funds obtained from the total savings in the economy[60].

We assume that all savings are spent on investment goods, at fixed investment shares for each sector, as expressed in the following equation[61]:

$$I_g = \frac{\bar{\theta}_{\mathrm{g}}}{P_g^Q} I \qquad \text{AI-60}$$

---

[60] There is an additional problem to the determination of the flow-of-funds related to the data available from the social accounting framework, since this structure does not include data about the determination of the total volume of investment and about its sector allocation. For the first problem, in the model described here, the exogenous savings rates to the income of each institution determine the total savings (and hence investment) endogenous (this is very similar to the economics classical theory of investment); meanwhile, for the second problem, the sector share parameters for investment ($\bar{\theta}_g$) are assumed fixed.

[61] Undoubtedly, one of the biggest discussion fields in economic theory is the causality determination between investments and savings decisions. However, it is valid to underline that these equations (in unison with equation **Error! Reference source not found.**) mainly reflect the accountability equality between savings-investments in the economy, especially under a static approach as the one assumed by this section. Capital flows, investment decisions, effective demand, and other issues have a much more dynamic feature and are more appropriate for dynamic models formulation.

AI.2.5 The extended market clearing and zero profit conditions

The market clearing obtained in the previous section have to be extended to include the new institution and the foreign trade participation in the markets. The resulting extended versions of the production factors and final products market clearing are represented bellow:

$$\sum_{s} Q_{pf,s} \le \bar{q}^{H}_{pf} + \bar{q}^{G}_{pf} \quad \perp \quad P_{pf} \tag{AI-61}$$

$$Q^{H}_{g} + \sum_{s} Q^{II}_{g,s} + I_{g} \le Q^{Q}_{g} \quad \perp \quad P^{Q}_{g} \tag{AI-62}$$

An additional market clearing condition is necessary to determine the savings investments market equilibrium.

$$I = S \tag{AI-63}$$

Finally, if we consider the above formulated behavior equations, zero profit conditions and market clearing conditions it is possible to assemble a set of equations to represent the open economy CGE model, as will be shown in the next sub section.

AI.2.6 The open economy CGE model

Considering the equations described in this section and additionally updating the previous section equations to include the respective taxes, transfers and propensities to save, the resulting list of variables present in our CGE open economy model can be represented by:

Variables:

	Household:
Q^{H}_{g}	Household domestic goods demand
P_{pf}	Price of production factor pf
Y^{H}	Total household income
	Productive sectors:
$Q_{pf,s}$	Quantity of production factor pf utilized in a specific sector s
Q^{VA}_{s}	Quantity of value added composite good produced by sector s
P^{VA}_{s}	Price of value added composite good of a specific sector s
$Q^{II}_{g,s}$	Quantity of intermediary input g utilized by a specific sector s

$\mathrm{Q}_{\mathrm{s}}^{\mathrm{S}}$	Quantity of the commodity produced by a specific sector s
$\mathrm{P}_{\mathrm{g}}^{\mathrm{S}}$	Price of commodity produced by a specific sector s (without foreign aggregations and production taxes)
	Imports Armington Aggregation:
$\mathrm{Q}_{\mathrm{g}}^{\mathrm{M}}$	Quantity of good g imported from the exterior
$\mathrm{Q}_{\mathrm{g}}^{\mathrm{D}}$	Quantity of aggregated imported and domestic produced supply of good g
$\mathrm{P}_{\mathrm{g}}^{\mathrm{D}}$	Price of Armington aggregated price of the good g
	Exports CET disaggregation:
$\mathrm{Q}_{\mathrm{g}}^{\mathrm{EX}}$	Quantity of goods g exported to the exterior
$\mathrm{Q}_{\mathrm{g}}^{\mathrm{Q}}$	Quantity of final domestic market supply of good g
$\mathrm{P}_{\mathrm{g}}^{\mathrm{Q}}$	Price of final domestic good g
	Government:
Y^{G}	Total government income
E^{G}	Total government expenditure
Y^{TAX}	Total government taxes income
	Savings and Investments
S	Total economy savings
S^{H}	Households savings
S^{G}	Government savings
$\mathrm{S}^{\mathrm{Ext}}$	Foreign total savings
I	Total investment
$\mathrm{Q}_{\mathrm{g}}^{\mathrm{I}}$	Quantity of good g demanded as investment good

, while the equations are listed below[62]:

Household behavior

$$Q_g^H = \frac{\bar{c}_g^H (1 - \bar{s}^H) Y^H}{(1 + \bar{tx}^H) P_g^Q} \quad , \forall g \tag{AI-8}$$

$$\begin{aligned} Y^H = \sum_{pf} P_{pf} \bar{q}_{pf}^H + \overline{transf}^{G-H} + \overline{transf}^{Ext-H} \\ + \overline{psc}^H \sum_s \bar{tx}_{s,pf=Labor}^{SC} P_{pf=Labor} Q_{pf=Labor,s} + \overline{transf}^{Ext-H} \end{aligned} \tag{AI-64}$$

$$S^H = \bar{s}^H Y^H \tag{AI-65}$$

---

[62] Some of the equations described below present changed terms or extensions departing from the original referenced equation in the text because of the inclusion of savings, taxes and transfers in their formulations.

Production sector behavior

$$\begin{aligned}&\left(Q_{pf=Labor,s}\right)^{\frac{1}{\bar{\sigma}_s^{VA}}}\left(1-\bar{a}_s^{VA_L}\right)\left(\left(1+\overline{tx}_{s,pf=Labor}^{SC}\right)P_{pf=labor}\right)\\&=\left(Q_{pf=Capital}\right)^{\frac{1}{\bar{\sigma}_s^{VA}}}\left(\bar{a}_s^{VA\_L}\right)\left(P_{pf=Capital}\right)\quad,\forall s\end{aligned}\tag{AI-16}$$

$$CES\left(Q_{pf,s}\right)-Q_s^{VA}=0\quad\perp\quad p_s^{VA}\quad,\forall s\tag{AI-17}$$

$$P_s^{VA}Q_s^{VA}=(1+\overline{tx}_s^{SC})P_{pf=Labor}Q_{pf=Labor,s}+P_{pf=Capital}Q_{pf=Capital,s}\quad,\forall s\tag{AI-18}$$

$$Q_s^S=\frac{Q_{g,s}^{II}}{\bar{c}_{g,s}^{II}}\quad\perp\quad Q_{g,s}^{II}\quad,\forall g,s\tag{AI-23}$$

$$Q_s^S=\frac{Q_s^{VA}}{\bar{c}_s^{VA}}\quad\perp\quad Q_s^{VA}\quad,\forall s\tag{AI-24}$$

$$\begin{aligned}&P_s^SQ_s^S+\overline{transf}_s^{G\_S}-P_s^{VA}Q_s^{VA}-\sum_g(1+\overline{tx}_s^{Pdct})P_gQ_{g,s}^{II}-\overline{emiss\ rate}_s^{CO2}\bar{p}^{CO2}Q_s^S\\&\leq 0\ \perp\ Q_s^S\geq 0\quad,\forall s\end{aligned}\tag{AI-25}$$

Imports Armington Aggregation

$$\left(\mathrm{Q_g^S}\right)^{\frac{1}{\bar{\sigma}_s^{VA}}}\left(1-\mathrm{\bar{a}}_\mathrm{g}^{D}\right)\left(\left(1+\mathrm{\overline{tx}_s^{Pdction}}\right)\mathrm{P_g^S}\right)=\left(\mathrm{Q_g^M}\right)^{\frac{1}{\bar{\sigma}_s^{VA}}}\left(\mathrm{\bar{a}}_\mathrm{g}^{D}\right)\left(\mathrm{\bar{p}_g^M}\right)\quad,\forall\mathrm{g}\tag{AI-42}$$

$$\mathrm{Q_g^D-CES\left(Q_g^S,Q_g^M\right)=0\perp\lambda_g^D}\quad,\forall\mathrm{g}\tag{AI-43}$$

$$\mathrm{P_g^DQ_g^D-\left(1+\overline{tx}_s^{Pdction}\right)P_g^SQ_g^S-\bar{p}_g^MQ_g^M=0}\quad,\forall\mathrm{g}\tag{AI-44}$$

Exports CET disaggrega

$$\left(\bar{b}_\mathrm{g}^{Q}\right)^{\bar{\sigma}_\mathrm{g}^{Q}}\left(\left(1+\mathrm{\overline{tx}_{Exp}^{Pdct}}\right)\mathrm{\bar{p}_g^{EX}}\right)^{\bar{\sigma}_\mathrm{g}^{Q}}\mathrm{Q_g^Q}=\left(1-\bar{b}_\mathrm{g}^{Q}\right)^{\bar{\sigma}_\mathrm{g}^{Q}}\left(\mathrm{P_g^Q}\right)^{\bar{\sigma}_\mathrm{g}^{Q}}\mathrm{Q_g^{EX}}\quad,\forall\mathrm{g}\tag{AI-51}$$

$$\mathrm{Q_g^D-CET\left(Q_g^Q,Q_g^{EX}\right)=0\ \perp\ \lambda_g^Q}\ ,\forall\mathrm{g}\tag{AI-52}$$

$$\mathrm{P_g^QQ_g^Q+\bar{p}_g^{EX}Q_g^{EX}-P_g^DQ_g^D=0}\quad,\forall\mathrm{g}\tag{AI-53}$$

Government

$$\mathrm{Y^G=\sum_{pf}P_{pf}\bar{q}_{pf}^G+\overline{transf}^{\,Ext-G}+Y^{TAX}}\tag{AI-54}$$

$$\begin{aligned}\mathrm{E^G}&=\mathrm{\sum_g(1+\overline{tx}^G)P_g^Q\bar{q}_g^G+\overline{transf}^{\,G-H}+\sum_s\overline{transf}_s^{\,G\_S}}\\&\quad+\mathrm{\overline{psc}^H\sum_s\overline{tx}_s^{SC}P_{pf=Labor}Q_{pf=Labor,s}}\end{aligned}\tag{AI-55}$$

$$\mathrm{Y^G-E^G=S^G}\tag{AI-56}$$

$$\begin{aligned}\mathrm{Y^{TAX}}&=\mathrm{\sum_s\overline{tx}_s^{SC}P_{pf=Labor}Q_{pf=Labor,s}+\sum_s\overline{tx}_s^{Pdction}P_g^SQ_g^S}\\&\quad+\sum_s\overline{emiss\ rate}_s^{CO2}\bar{p}^{CO2}Q_s^S+\mathrm{\sum_{s,g}\overline{tx}_s^{Pdct}P_g^QQ_{g,s}^{II}}\\&\quad+\mathrm{\sum_g\overline{tx}^HP_g^QQ_g^H+\sum_g\overline{tx}^GP_g^Q\bar{q}_g^G+\sum_g\overline{tx}^{Inv}P_g^QQ_g^I}\\&\quad+\mathrm{\sum_g\overline{tx}^{Exp}P_g^{EX}Q_g^{EX}}\end{aligned}\tag{AI-57}$$

Savings and Investments

$$\mathrm{S=S^H+S^G+S^{Ext}+\overline{transf}^{\,Ext\_K}}\tag{AI-58}$$

$$\begin{aligned}\mathrm{S^{Ext}}&=\mathrm{\sum_g\bar{p}_g^MQ_g^M-\sum_g\left(1+\overline{tx}_{Exp}^{Pdct}\right)\bar{p}_g^{EX}Q_g^{EX}-\overline{transf}^{\,Ext-G}-\overline{transf}^{\,Ext-H}}\\&\quad-\mathrm{\overline{transf}^{\,Ext\_K}}\end{aligned}\tag{AI-59}$$

$$\mathrm{Q_g^I=\frac{\bar{\theta}_g}{(1+\overline{tx}^{Inv})P_g^Q}I}\quad,\forall\mathrm{g}\tag{AI-60}$$

Market clearing conditions

$$\mathrm{\sum_sQ_{pf,s}\leq\bar{q}_{pf}^H+\bar{q}_{pf}^G\quad\perp\quad P_{pf}}\quad,\forall\mathrm{pf}\tag{AI-61}$$

$$\mathrm{Q_g^H+\bar{q}_g^G+\sum_sQ_{g,s}^{II}+Q_g^I\leq Q_g^Q\quad\perp\quad P_g^Q}\quad,\forall\mathrm{g}\tag{AI-62}$$

$$\mathrm{I} = \mathrm{S} \qquad \text{AI-63}$$

, where:

$$\mathrm{CES}\left(\mathrm{Q_{pf,s}}\right) = \mathrm{Q}_{\mathrm{s}}^{VA} = \bar{\alpha}_{\mathrm{s}}^{VA}\left(\sum\nolimits_{\mathrm{pf}} \bar{\mathrm{a}}_{\mathrm{pf,s}}^{VA} \mathrm{Q}_{\mathrm{pf,s}}^{\frac{\bar{\sigma}_{\mathrm{s}}^{VA}-1}{\bar{\sigma}_{\mathrm{s}}^{VA}}}\right)^{\frac{\bar{\sigma}_{\mathrm{s}}^{VA}}{\bar{\sigma}_{\mathrm{s}}^{VA}-1}};$$

$$\mathrm{CES}\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{S}}, \mathrm{Q}_{\mathrm{g}}^{\mathrm{M}}\right) = \mathrm{Q}_{\mathrm{g}}^{\mathrm{D}} = \bar{\alpha}_{\mathrm{g}}^{D}\left(\bar{\mathrm{a}}_{\mathrm{g}}^{D} \mathrm{Q}_{\mathrm{g}}^{\mathrm{S}\,\frac{\bar{\sigma}_{\mathrm{g}}^{D}-1}{\bar{\sigma}_{\mathrm{g}}^{D}}} + \left(1-\bar{\mathrm{a}}_{\mathrm{g}}^{D}\right)\mathrm{Q}_{\mathrm{g}}^{\mathrm{M}\,\frac{\bar{\sigma}_{\mathrm{g}}^{D}-1}{\bar{\sigma}_{\mathrm{g}}^{D}}}\right)^{\frac{\bar{\sigma}_{\mathrm{g}}^{D}}{\bar{\sigma}_{\mathrm{g}}^{D}-1}};$$

$$\mathrm{CET}\left(\mathrm{Q}_{\mathrm{g}}^{\mathrm{Q}}, \mathrm{Q}_{\mathrm{g}}^{\mathrm{EX}}\right) = \mathrm{Q}_{\mathrm{g}}^{\mathrm{D}} = \bar{\beta}_{\mathrm{g}}^{Q}\left(\bar{b}_{\mathrm{g}}^{Q} \mathrm{Q}_{\mathrm{g}}^{\mathrm{Q}\,\frac{\bar{\sigma}_{\mathrm{g}}^{Q}+1}{\bar{\sigma}_{\mathrm{g}}^{Q}}} + \left(1-\bar{b}_{\mathrm{g}}^{Q}\right)\mathrm{Q}_{\mathrm{g}}^{\mathrm{EX}\,\frac{\bar{\sigma}_{\mathrm{g}}^{Q}+1}{\bar{\sigma}_{\mathrm{g}}^{Q}}}\right)^{\frac{\bar{\sigma}_{\mathrm{g}}^{Q}}{\bar{\sigma}_{\mathrm{g}}^{Q}+1}}.$$

As can be seen, the model sustains fourteen endogenous variables in $\mathbb{R}^{\mathrm{g}(=\mathrm{s})}$, nine in $\mathbb{R}$, one in $\mathbb{R}^{\mathrm{pf}}$, one in $\mathbb{R}^{\mathrm{pfxs}}$, and one in $\mathbb{R}^{\mathrm{ixj}}$. At the same time, our CGE model is composed by fifteen equations of g (=s) dimensions, ten of one dimension, one of pf dimensions, one of pfxs dimensions, and one of ixj dimension.

Therefore, the CGE model presented is a square system of equations. Once more we adopt a commodity price as a “numéraire” because, accordingly to Walras law, one equation is functionally dependent on the others.

AI.2.7 Defining the model parameters

In order to apply the developed CGE model to an actual economy we need to determine the value of each parameter described in the equation system. The updated model parameters list is the following:

Parameters:

	Household Behavior:
$\bar{\mathrm{q}}_{\mathrm{pf}}^{\mathrm{H}}$	Quantity of production factor pf initially owned by the representative household
$\bar{\mathrm{c}}_{\mathrm{g}}^{\mathrm{H}}$	Representative household marginal propensity to consume domestic good g
$\bar{\mathrm{s}}^{\mathrm{H}}$	Representative Household marginal propensity to save
$\overline{\mathrm{psc}}^{\mathrm{H}}$	Proportion of annual social contribution payments reverted directly to households
	Productive sector parameters:
$\bar{\alpha}_{s}^{VA}$	Productivity parameter of sector value added composite good production function
$\bar{\mathrm{a}}_{s,pf}^{VA}$	Share parameter of product factor on value added composite good production function
$\bar{\sigma}_{s}^{VA}$	Elasticity of substitution between productive factors of sector s

$\bar{c}^{II}_{g,s}$	Share parameter of intermediate composites inputs g on sector s production function
$\bar{c}^{VA}_{s}$	Share parameter of value added composite input on sector s production function
$\overline{emiss\ rate}^{CO2}_{s}$	CO2 emission rate of sectors belonging to the Emission Trading System (ETS)
	Imports Armington Aggregation:
$\bar{\alpha}^{D}_{g}$	Productivity parameter of Armington aggregated imported and domestic produced supply of good g
$\bar{a}^{D}_{g}$	Share parameter of domestic produced supply on Armington aggregate
$\bar{\sigma}^{D}_{g}$	Elasticity of substitution between imported and domestic produced good g
	Exports CET disaggregation:
$\bar{\beta}^{Q}_{g}$	Productivity parameter of CET export and domestically destined good g
$\bar{b}^{Q}_{g}$	Share parameter of CET domestically destined good g
$\bar{\sigma}^{Q}_{g}$	Elasticity of transformation between domestic and external destined supply
	Government Behavior:
$\bar{q}^{G}_{pf}$	Quantity of production factor pf initially owned by the government
$\bar{q}^{G}_{g}$	Government initial demand for good g
	Transfers:
$\overline{transf}^{G-H}$	Net transfers from the government to the households
$\overline{transf}^{Ext-G}$	Net transfers from the exterior to the government
$\overline{transf}^{Ext-H}$	Net transfers from the exterior to the households
$\overline{transf}^{Ext\_K}$	Net capital transfers from the exterior
$\overline{transf}^{G\_S}_{s}$	Net transfers from government to productive sector s (used to assign CO2 emission allowances for sectors in the ETS)
	Taxes:
$\bar{tx}^{SC}_{s}$	Social contribution tax rate
$\bar{tx}^{Pdction}_{s}$	Production tax rate
$\bar{tx}^{Pdct}_{s}$	Intermediate inputs product tax rate by sector
$\bar{tx}^{H,G,I,EX}$	Household, Government, Investment and Exports final goods tax rate
	Saves-Investments:
$\bar{\theta}_{g}$	Share parameter of demand for investment good g

	Prices:
$\bar{p}_g^{M}$	International price of the imported good g
$\bar{p}_g^{EX}$	International price of exported good g
$\bar{p}^{CO2}$	CO2 price

The substitution and transformation elasticity parameters are estimated from historical production and trade information. Following section AI.1.5.2, all prices can be set to one because the CGE model is relative in prices. Consequently, all initial quantities, endowments, transfers and tax rates can be direct obtained from the SAM accountability. Finally, through simple algebra manipulation the previously defined parameters are capable to give numbers to the CES and CET productive and share parameters.

Annex II The Extended Social Accounting Matrix

A schematic representation of a Social Accountability Matrix necessary for building a typical general equilibrium model can be seen in Figure 11. The electricity related expenditures and receipts representing the economy flow of uses and resources of this sector and products are underlined on the figure.

Figure 11. Schematic social accountability matrix[63].

		Expenditures						
		Q	Electricity	Factors	Taxes	Institutions	Savings-Investments	Exports
Receipts	Q		$\overline{e\_ii}_{gne}^{elet}$	-	-		-	
	Electricity	$\overline{e\_ii}_{sne}^{elet}$	$\overline{e\_ii}^{elet,elet}$	-	-	$\overline{e\_inst}^{elet}$	-	$\overline{e\_ex}^{elet}$
	Factors		$\overline{e\_pf}_{pf}^{elet}$	-	-	-	-	-
	Taxes		$\overline{e\_tax}_{tx}^{elet}$	-	-			
	Institutions	-	$\overline{e\_allow}^{elet}$				-	
	Savings-Investments	-	-	-	-		-	
	Imports		$\overline{e\_m}^{elet}$	-	-			-

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

An Extended Social Accountability Matrix capable of representing the different electricity activities - GEN (Generation) and TD&O (Transmission, Distribution and Other activities) - and their location and time heterogeneity must be able to reproduce the exact figures present at the original SAM (Figure 11), while introducing the additional electricity detail representation. A schematic representation of the extended SAM with this information can be seen in Figure 12.

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[63] Smaller lowercase letters with a bar above represent parameters, while capital letters represent the variables of the calibration model.

Figure 12. Schematic social accountability matrix with electricity detail represented.

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

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

Analyzing the electricity receipts represented at the extended SAM (the electricity row in Figure 12) it can be seen that the final electricity product is divided into two different products roughly representing the energy and the network components of the electricity activity. Due to the presence of congestions, network constraints, different regulation schemes and different market structures in the national borders, these products are differentiated by location (location 1 … location n). Additionally, and mostly important for the electricity generation behavior, the electricity products are further disaggregated by their time of consumption (periods and load blocks)[64,65].

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

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

Each location and time period has its own differentiated production structure in the electricity generation activity (GEN). This is necessary to reflect the different technology portfolios used at different time periods and, most importantly, the change in the production behavior of the same generation technology with time. This happens because the same electricity production technology can act differently according to different demand and price levels. The clearest example of this behavior is given by the generation units capable of storage (pumping units for example) that

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

[65] This thesis methodology focused on explaining the introduction of generation activity detail on CGE models. This option is made to avoid the excessive length needed for addressing the TD&O and capacity component of the electricity activity in detail. However, introducing time heterogeneity for the contracted electricity power and different costs representation for the TD&O activity would require following a similar approach as the introduction of energy disaggregation into load blocks, load levels and different generation technologies.

act as demanders in lower price periods and suppliers at higher prices periods. This differentiated behavior in time could also be derived from specific technological characteristics of the unit cycling behavior, spinning reserve requirements, ramp constraints, production intermittence and other technical characteristics when comparing peak and off peak load periods.

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

Annex III The Calibration Model

AIII.1 Sets, parameters and variables

Sets:

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

Variables:

Objective variables to be calibrated:

$\text{OeM\_VOM}_{y,t}$	calibrated operation and maintenance variable costs (€/MWh)
$\text{OeM\_FOM}_{y,l,t}^{labor}$	calibrated operation and maintenance labor fixed costs (€/KW)
$\text{OeM\_FOM}_{y,l,t}^{sc}$	calibrated operation and maintenance social contribution fixed costs (€/KW)
$\text{OeM\_FOM}_{y,l,t}^{equip}$	calibrated operation and maintenance equipment fixed costs (€/KW)
$\eta_{y,l,t}$	calibrated thermodynamic efficiency (MWh/kg)
OWN_CONS	Calibrated own consumption of electricity by the generation activity (%)
$\text{OVERN\_COSTS}_{y,t}$	calibrated overnight new capacity investment costs (€/KW)
$\text{LOSS}_{y,l,p,b}$	Transmission and distributions losses proportion (%)
$\text{CO2e\_CONTENT}_{y,t,f}$	CO2e content in emissions of technology t using fuel f

	(MMtCO2e/ MWh)
$P\_IMP\_ADJ_{\mathrm{y,l.dp,db}}$	Adjustment factor for observed imported electricity prices (p.u.)
$P\_EXP\_ADJ_{\mathrm{y,l.dp,db}}$	Adjustment factor for observed exported electricity prices (p.u.)

Objective deviation variable to be minimized

$\mathrm{MAX\_PCTG\_DEV}_{y}^{c}$	Maximum percentage deviation of calibrated variables (%)

Deviations of the calibrated variables:

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

Electricity extended SAM cell accounts:

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

$E\_II\_EQ\_POWER_{y,sne}$	Non electric sector network payments for electricity (Electricity extended SAM) (millions €)
$E\_I\_POWER_{y,i}$	Institutions final consumption for electricity network services (Electricity extended SAM) (millions €)
$E\_EX\_POWER_{y}$	Exports network payments for electricity (Electricity extended SAM) (millions €)

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

FIX_*	Fixed costs component for each of the above electricity extended cell accounts (millions €)
VAR_*	Variable costs component for each of the above electricity extended cell accounts (millions €)
$TOTAL\_SURPLUS_{y,l,gp,gb}$	Total generation economic surplus by load block after excluded variable costs (millions €)

Parameters:

Original SAM cells:

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

Initial values of technological parameters used in the calibration:

$\overline{oem\_vom}_{y,t}$	Operation and maintenance variable costs (€/MWh)
$\overline{oem\_fom}^{labor}_{y,l,t}$	Operation and maintenance labor fixed costs (€/KW)
$\overline{oem\_fom}^{sc}_{y,l,t}$	Operation and maintenance social contribution fixed costs (€/KW)
$\overline{oem\_fom}^{equip}_{y,l,t}$	Operation and maintenance equipment fixed costs (€/KW)
$\bar{\eta}_{y,l,t}$	Thermodynamic efficiency (MWh/kg)
$\overline{own\_cons}$	Initial own consumption of electricity by the generation activity (%)
$\overline{overn\_costs}_{y,t}$	Overnight new capacity investment costs (€/KW)
$\overline{loss}_{y,l,p,b}$	Transmission and distributions losses proportion (%)
$\overline{co2}^{fuel\_content}_{t,f}$	CO2 emission potential by combustible (MMtCO2e/ MWh)

Auxiliary parameters:

$\overline{\text{pgen}}_{\text{y,t,f,l,gp,gb}}$	Electricity power generation by each technology (MW)
$\overline{\text{tcap}}_{\text{y,l,t}}$	Total installed capacity potency (MW)
$\overline{\text{ppumped}}_{\text{y,l,p,b}}$	Pumping consumed electricity power (MW)
$\overline{\text{pins}}_{\text{y}',\text{l,t}}$	New installed capacity by year (MW)
$\bar{\text{p}}^{\text{energy only}}_{\text{y,l.dp,db}}$	Energy only electricity price by block (€/MW)
$\overline{\text{dist\_factor}}_{\text{y,l,p,b}}$	Factor responsible to distribute the fixed cost payments between the different load blocks and periods according their respective generation economic surplus (%)
$\overline{\text{tx\_aliq}}_{\text{tx}}$	Electricity taxes aliquot (%)
$\overline{\text{demand\_by\_agent}}_{\text{y,SAM,l,dp,db}}$	electricity demanded by agent described in the SAM (MWh)
$\overline{\text{dur}}_{\text{l,p,b}}$	load block duration (hours)
$\overline{\text{cap}}^{\text{to\_be\_amort}}_{\text{y,l,t}}$	power plant technology existent installed capacity not amortized (including exclusion of installed capacity previous liberalization, 1997, considered already paid as stranded costs) (MW)
$\bar{\text{p}}^{\text{fuel}}_{\text{y,p,t,f}}$	fuel price: enriched uranium (€/Kg), coal (€/t), gas natural (€/miles m3) and fuel-oil (€/t diesel)
$\overline{\text{pimp}}_{\text{y,l,p,b}}$	Generated potency imported (MWh)
$\overline{\text{idc}}_{\text{t}}$	accumulated interest during construction (p.u.)
$\overline{\text{crf}}_{\text{t}}$	Capital recovery factor, i.e., accumulated discount payments during amortization (p.u.)
$\bar{\text{p}}^{\text{CO2}}_{\text{y}}$	co2 price (€/tCO2)
$\overline{\text{rights}}^{\text{CO2}}_{\text{y,l,t}}$	technology emission rights given by the government (MMtCO2e)

AIII.2 Calibration model equations

Objective function: $\text{Min} \quad \sum_c \text{MAX\_PCTG\_DEV}_y^c$ AIII-1

Subject to:

First Group: Chebyshev deviation equations:

Variable O&M costs:

$$\text{OeM\_VOM}_{\text{y,t}} - \overline{\text{oem\_vom}}_{\text{y,t}} + \text{N\_DEV\_OeM\_VOM}_{\text{y,t}} - \text{P\_DEV\_OeM\_VOM}_{\text{y,t}} = 0 \qquad \text{AIII-2}$$

$$\frac{\text{N\_DEV\_OeM\_VOM}_{\text{y,t}} + \text{P\_DEV\_OeM\_VOM}_{\text{y,t}}}{\overline{\text{oem\_vom}}_{\text{y,t}}} \leq \text{MAX\_PCTG\_DEV}_y^{\text{OeM\_VOM}} \qquad \text{AIII-3}$$

Fixed O&M labor:

$$\text{OeM\_FOM}^{\text{labor}}_{\text{y,l,t}} - \overline{\text{oem\_fom}}^{\text{labor}}_{\text{y,l,t}} + \text{N\_DEV\_OeM\_FOM}^{\text{labor}}_{\text{y,l,t}} - \text{P\_DEV\_OeM\_FOM}^{\text{labor}}_{\text{y,l,t}} = 0 \tag{AIII-4}$$

$$\frac{\text{N\_DEV\_OeM\_FOM}^{\text{labor}}_{\text{y,l,t}} + \text{P\_DEV\_OeM\_FOM}^{\text{labor}}_{\text{y,l,t}}}{\overline{\text{oem\_fom}}^{\text{labor}}_{\text{y,l,t}}} \le \text{MAX\_PCTG\_DEV}_y^{\text{OeM\_FOM}^{labor}} \tag{AIII-5}$$

Fixed O&M taxes costs:

$$\text{OeM\_FOM}^{\text{sc}}_{\text{y,l,t}} - \overline{\text{oem\_fom}}^{\text{sc}}_{\text{y,l,t}} + \text{N\_DEV\_OeM\_FOM}^{\text{sc}}_{\text{y,l,t}} - \text{P\_DEV\_OeM\_FOM}^{\text{sc}}_{\text{y,l,t}} = 0 \tag{AIII-6}$$

$$\frac{\text{N\_DEV\_OeM\_FOM}^{\text{sc}}_{\text{y,l,t}} + \text{P\_DEV\_OeM\_FOM}^{\text{sc}}_{\text{y,l,t}}}{\overline{\text{oem\_fom}}^{\text{sc}}_{\text{y,l,t}}} \le \text{MAX\_PCTG\_DEV}_y^{\text{OeM\_FOM}^{sc}} \tag{AIII-7}$$

Fixed O&M equipment costs:

$$\text{OeM\_FOM}^{\text{equip}}_{\text{y,l,t}} - \overline{\text{oem\_fom}}^{\text{equip}}_{\text{y,l,t}} + \text{N\_DEV\_OeM\_FOM}^{\text{equip}}_{\text{y,l,t}} - \text{P\_DEV\_OeM\_FOM}^{\text{equip}}_{\text{y,l,t}} = 0 \tag{AIII-8}$$

$$\frac{\text{N\_DEV\_OeM\_FOM}^{\text{equip}}_{\text{y,l,t}} + \text{P\_DEV\_OeM\_FOM}^{\text{equip}}_{\text{y,l,t}}}{\overline{\text{oem\_fom}}^{\text{equip}}_{\text{y,l,t}}} \le \text{MAX\_PCTG\_DEV}_y^{\text{OeM\_FOM}^{\text{equip}}} \tag{AIII-9}$$

Thermodynamic efficiency:

$$\eta_{\text{y,t,f}} - \bar{\eta}_{\text{y,t,f}} + \text{N\_DEV\_}\eta_{\text{y,t,f}} - \text{P\_DEV\_}\eta_{\text{y,t,f}} = 0 \tag{AIII-10}$$

$$\frac{\text{N\_DEV\_}\eta_{\text{y,t,f}} + \text{P\_DEV\_}\eta_{\text{y,t,f}}}{\bar{\eta}_{\text{y,t,f}}} \le \text{MAX\_PCTG\_DEV}_y^{\eta} \tag{AIII-11}$$

Generation technologies own electricity consumption:

$$\text{OWN\_CONS} - \overline{\text{own\_cons}} + \text{N\_DEV\_OWN\_CONS} - \text{P\_DEV\_OWN\_CONS} = 0 \tag{AIII-12}$$

$$\frac{\text{N\_DEV\_OWN\_CONS} + \text{P\_DEV\_OWN\_CONS}}{\overline{\text{own\_cons}}} \le \text{MAX\_PCTG\_DEV}_y^{\text{OWN\_CONS}} \tag{AIII-13}$$

New capacity overnight investment costs:

$$\begin{aligned}\text{OVERN\_COSTS}_{\text{y,t}} - \overline{\text{overn\_costs}}_{\text{y,t}} &+ \text{N\_DEV\_OVERN\_COSTS}_{\text{y,t}} \\ &- \text{P\_DEV\_OVERN\_COSTS}_{\text{y,t}} = 0\end{aligned} \tag{AIII-14}$$

$$\frac{\text{N\_DEV\_OVERN\_COSTS}_{\text{y,t}} + \text{P\_DEV\_OVERN\_COSTS}_{\text{y,t}}}{\overline{\text{overn\_costs}}_{\text{y,t}}} \le \text{MAX\_PCTG\_DEV}_y^{\text{OVERN\_COSTS}} \tag{AIII-15}$$

TD&O losses proportion:

$$\mathrm{LOSS}_{\mathrm{y,l,p,b}} - \overline{\mathrm{loss}}_{\mathrm{y,l,p,b}} + \mathrm{N\_DEV\_LOSS}_{\mathrm{y,l,p,b}} - \mathrm{P\_DEV\_LOSS}_{\mathrm{y,l,p,b}} = 0 \tag{AIII-16}$$

$$\frac{\mathrm{N\_DEV\_LOSS}_{\mathrm{y,l,p,b}} + \mathrm{P\_DEV\_LOSS}_{\mathrm{y,l,p,b}}}{\overline{\mathrm{loss}}_{\mathrm{y,l,p,b}}} \leq \mathrm{MAX\_PCTG\_DEV}_{y}^{\mathrm{LOSS}} \tag{AIII-17}$$

CO2e content by generation technology and fuel type used:

$$\begin{aligned}\mathrm{CO2e\_CONTENT}_{\mathrm{y,t,f}} - \overline{\mathrm{co2}}_{\mathrm{t,f}}^{\mathrm{fuel\_content}} &+ \mathrm{N\_DEV\_CO2e\_CONTENTS}_{\mathrm{y,t,f}} \\ &- \mathrm{P\_DEV\_CO2e\_CONTENTS}_{\mathrm{y,t,f}} = 0\end{aligned} \tag{AIII-18}$$

$$\begin{aligned}&\frac{\mathrm{N\_DEV\_CO2e\_CONTENTS}_{\mathrm{y,t,f}} + \mathrm{P\_DEV\_CO2e\_CONTENTS}_{\mathrm{y,t,f}}}{\overline{\mathrm{co2}}_{\mathrm{t,f}}^{\mathrm{fuel\_content}}} \\ &\qquad \leq \mathrm{MAX\_PCTG\_DEV}_{y}^{\mathrm{CO2e\_CONTENT}}\end{aligned} \tag{AIII-19}$$

Export Price adjust (difference between internal market prices and export prices):

$$\mathit{P\_EXP\_ADJ}_{\mathrm{y,l.dp,db}} - 1 + \mathrm{N\_DEV\_}\mathit{P\_EXP\_ADJ}_{\mathrm{y,l.dp,db}} - \mathrm{P\_DEV\_}\mathit{P\_EXP\_ADJ}_{\mathrm{y,l.dp,db}} = 0 \tag{AIII-20}$$

$$\mathrm{N\_DEV\_}\mathit{P\_EXP\_ADJ}_{\mathrm{y,l.dp,db}} + \mathrm{P\_DEV\_}\mathit{P\_EXP\_ADJ}_{\mathrm{y,l.dp,db}} \leq \mathrm{MAX\_PCTG\_DEV}_{y}^{\mathit{P\_EXP\_ADJ}} \tag{AIII-21}$$

Import Price adjust (difference between internal market prices and export prices):

$$\mathit{P\_IMP\_ADJ}_{\mathrm{y,l.dp,db}} - 1 + \mathrm{N\_DEV\_}\mathit{P\_IMP\_ADJ}_{\mathrm{y,l.dp,db}} - \mathrm{P\_DEV\_}\mathit{P\_IMP\_ADJ}_{\mathrm{y,l.dp,db}} = 0 \tag{AIII-22}$$

$$\mathrm{N\_DEV\_}\mathit{P\_IMP\_ADJ}_{\mathrm{y,l.dp,db}} + \mathrm{P\_DEV\_}\mathit{P\_IMP\_ADJ}_{\mathrm{y,l.dp,db}} \leq \mathrm{MAX\_PCTG\_DEV}_{y}^{\mathit{P\_IMP\_ADJ}} \tag{AIII-23}$$

Second Group: SAM 'Must follow' accountability constraints**:**

$$\overline{\mathit{e\_ii}}_{y,gne}^{elet} = \mathrm{E\_II\_QE\_TDeO}_{\mathrm{y,gne}} + \sum_{\mathrm{l,gp,gb,t}} \mathrm{E\_II\_QE\_GEN}_{\mathrm{y,gne,l,gp,gb,t}} \tag{AIII-24}$$

$$\overline{\mathit{e\_pf}}_{y,pf}^{elet} = \mathrm{E\_F\_E\_TDeO}_{\mathrm{y,pf}} + \sum_{\mathrm{l,gp,gb,t}} \mathrm{E\_F\_E\_GEN}_{\mathrm{y,pf,l,gp,gb,t}} \tag{AIII-25}$$

$$\overline{\mathit{e\_tax}}_{y,tx}^{elet} = \mathrm{E\_TAX\_E\_TDeO}_{\mathrm{y,tx}} + \sum_{\mathrm{l,gp,gb,t}} \mathrm{E\_TAX\_E\_GEN}_{\mathrm{y,tx,l,gp,gb,t}} \tag{AIII-26}$$

$$\overline{\mathit{e\_m}}_{y}^{elet} = \mathrm{E\_M\_E\_TDeO}_{\mathrm{y}} + \sum_{\mathrm{l,gp,gb}} \mathrm{E\_M\_E\_GEN}_{\mathrm{y,l,gp,gb}} \tag{AIII-27}$$

$$\overline{e\_ii}_{y,sne}^{elet} = \text{E\_II\_EQ\_POWER}_{\text{y,sne}} + \sum_{\text{l,dp,db}} \text{E\_II\_EQ\_ENERGY}_{\text{y,sne,l,dp,db}} \tag{AIII-28}$$

$$\overline{e\_inst}_{y}^{elet} = \text{E\_I\_POWER}_{\text{y,i}} + \sum_{\text{l,dp,db}} \text{E\_I\_ENERGY}_{\text{y,i,l,dp,db}} \tag{AIII-29}$$

$$\overline{e\_ex}_{y}^{elet} = \text{E\_EX\_POWER}_{\text{y}} + \sum_{\text{l,dp,db}} \text{E\_EX\_ENERGY}_{\text{y,l,dp,db}} \tag{AIII-30}$$

Third Group: Micro-founded macroeconomic aggregates:

Electricity generation sector fuel and equipment intermediate inputs demand:

$$\begin{aligned} &\text{E\_II\_QE\_GEN}_{\text{y,gne,l,gp,gb,t}} \\ &\qquad = \text{VAR\_E\_II\_QE\_GEN}_{\text{y,gne,l,gp,gb,t}} \\ &\qquad + \overline{\text{dist\_factor}}_{\text{y,l,p,b}} \text{FIX\_E\_II\_QE\_GEN}_{\text{y,gne,l,t}} \end{aligned} \tag{AIII-31}$$

$$\text{VAR\_E\_II\_QE\_GEN}_{\text{y,gne,l,gp,gb,t}} = \frac{\eta_{\text{y,l,t}}\ \bar{\text{p}}_{\text{y,p,t,f}}^{\text{fuel}} \left(\sum_{\text{f}} \overline{\text{pgen}}_{\text{y,t,f,l,gp,gb}}\right) \overline{\text{dur}}_{\text{l,gp,gb}}}{10^6} \tag{AIII-32}$$

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

$$\begin{aligned} \text{VAR\_E\_II\_QE\_GEN}_{\text{y,gne,l,gp,gb,t}} &= \frac{\text{OeM\_VOM}_{\text{y,t}} \left(\sum_{\text{f}} \overline{\text{pgen}}_{\text{y,t,f,l,gp,gb}}\right) \overline{\text{dur}}_{\text{l,gp,gb}}}{10^6}\ \text{gne} \\ &= \text{manufactures sector} \end{aligned} \tag{AIII-33}$$

$$\text{FIX\_E\_II\_QE\_GEN}_{\text{y,gne,l,t}} = \frac{\left(\text{OeM\_FOM}_{\text{y,l,t}}^{\text{equip}}\right) \overline{\text{tcap}}_{\text{y,l,t}}}{10^3} \qquad \text{gne} = \text{manufactures sector} \tag{AIII-34}$$

Electricity generation sector demand for electricity:

$$\text{E\_II\_EE\_GEN}_{\text{y,l,dp,dbgp,gb,t}} = \text{VAR\_E\_II\_EE\_GEN}_{\text{y,l,dp,dbgp,,gb,t}} \tag{AIII-35}$$

$$\begin{aligned} &\text{VAR\_E\_II\_EE\_GEN}_{\text{y,l,dp,db,gp,gb,t}} \\ &\qquad = \frac{\text{OWN\_CONS} \left(\sum_{\text{f}} \overline{\text{pgen}}_{\text{y,t,f,l,gp,gb}}\right) \overline{\text{dur}}_{\text{l,gp,gb}} \bar{\text{p}}_{\text{y,l.dp,db}}^{\text{energy only}}}{10^6} \\ &\qquad + \frac{\overline{\text{ppumped}}_{\text{y,l,p,b}} \overline{\text{dur}}_{\text{l,gp,gb}} \bar{\text{p}}_{\text{y,l.dp,db}}^{\text{energy only}}}{10^6} \end{aligned} \tag{AIII-36}$$

Electricity generation sector demand for production factors:

$$\text{E\_F\_E\_GEN}_{\text{y,pf,l,gp,gb,t}} = \overline{\text{dist\_factor}}_{\text{y,l,gp,gb}} \overline{\text{dur}}_{\text{l,gp,gb}} \text{FIX\_E\_F\_E\_GEN}_{\text{y,pf,l,t}} \tag{AIII-37}$$

$$\mathrm{FIX\_E\_F\_E\_GEN}_{\mathrm{y,pf,l,t}} = \frac{\left(\mathrm{OeM\_FOM}_{\mathrm{y,l,t}}^{\mathrm{labor}}\right)\overline{\mathrm{tcap}}_{\mathrm{y,l,t}}}{10^3} \qquad \mathrm{pf} = \mathrm{Labor} \tag{AIII-38}$$

$$\begin{aligned}\mathrm{FIX\_E\_F\_E\_GEN}_{\mathrm{y,pf,l,t}} \\ &= \frac{\mathrm{OVERN\_COSTS}_{\mathrm{y,t}}\overline{\mathrm{idc}}_{\mathrm{t}}\overline{\mathrm{crf}}_{\mathrm{t}}\left(\overline{\mathrm{cap}}_{\mathrm{y,l,t}}^{\mathrm{to\_be\_amort}} + \sum_{\substack{\mathrm{y'\leq y} \\ \mathrm{y`\geq y-l\_t}}} \overline{\mathrm{pins}}_{\mathrm{y',l,t}}\right)}{10^3} \quad \mathrm{pf} \\ &= \mathrm{Capital}\end{aligned} \tag{AIII-39}$$

Electricity generation sector taxes:

$$\begin{aligned}\mathrm{E\_TAX\_E\_GEN}_{\mathrm{y,tx,l,gp,gb,t}} \\ &= \mathrm{VAR\_E\_TAX\_E\_GEN}_{\mathrm{y,tx,l,gp,gb,t}} \\ &+ \overline{\mathrm{dist\_factor}}_{\mathrm{y,l,p,b}}\mathrm{FIX\_E\_TAX\_E\_GEN}_{\mathrm{y,tx,l,t}} \\ &+ \overline{\mathrm{dist\_factor}}_{\mathrm{y,l,p,b}}\left(\overline{e\_tax}_{y,tx}^{elet}\right)_{if\ tx=Production\,Tax}\end{aligned} \tag{AIII-40}$$

$$\begin{aligned}\mathrm{VAR\_E\_TAX\_E\_GEN}_{\mathrm{y,tx,l,gp,gb,t}} \\ = \frac{\overline{\mathrm{tx\_aliq}}_{\mathrm{tx}}\left(\sum_{gne}\mathrm{E\_II\_QE\_GEN}_{\mathrm{y,gne,l,gp,gb,t}} + \sum_{dp,db}\mathrm{E\_II\_EE\_GEN}_{\mathrm{y,l,dp,db,gp,gb,t}}\right)}{10^6} \\ \mathrm{tx} = \mathrm{Product\ tax}\end{aligned} \tag{AIII-41}$$

$$\begin{aligned}\mathrm{VAR\_E\_TAX\_E\_GEN}_{\mathrm{y,tx,l,gp,gb,t}} = \sum_{f}\mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}}\,\overline{\mathrm{co2}}_{\mathrm{t,f}}^{\mathrm{fuel\_content}}\,\bar{\mathrm{p}}_{\mathrm{y}}^{\mathrm{CO2}}\overline{\mathrm{dur}}_{\mathrm{l,p,b}} \qquad \mathrm{tx} \\ = \mathrm{CO2\ payments}\end{aligned} \tag{AIII-42}$$

$$\mathrm{FIX\_E\_TAX\_E\_GEN}_{\mathrm{y,tx,l,t}} = \frac{\left(\mathrm{OeM\_FOM}_{\mathrm{y,l,t}}^{\mathrm{sc}}\right)\overline{\mathrm{tcap}}_{\mathrm{y,l,t}}}{10^3} \qquad \mathrm{tx} = \mathrm{Social\ contributions} \tag{AIII-43}$$

Electricity generation sector electricity imports payments:

$$\mathrm{E\_M\_E\_GEN}_{\mathrm{y,l,gp,gb}} = \mathrm{VAR\_E\_M\_E\_GEN}_{\mathrm{y,l,gp,gb}} \tag{AIII-44}$$

$$\mathrm{VAR\_E\_M\_E\_GEN}_{\mathrm{y,l,gp,gb}} = \frac{\overline{\mathrm{pimp}}_{\mathrm{y,l,p,b}}\,\overline{\mathrm{dur}}_{\mathrm{l,gp,gb}}\bar{\mathrm{p}}_{\mathrm{y,l.dp,db}}^{\mathrm{energy\ only}}P\_IMP\_ADJ_{\mathrm{y,l.dp,db}}}{10^6} \tag{AIII-45}$$

Electricity generation receipts from other productive sectors, institutions and exports:

$$\mathrm{E\_II\_EQ\_ENERGY}_{\mathrm{y,sne,l,dp,db}} = \frac{\overline{\mathrm{demand\_by\_agent}}_{\mathrm{y,sne,l,dp,db}}\overline{\mathrm{dur}}_{\mathrm{l,gp,gb}}\bar{\mathrm{p}}_{\mathrm{y,l.dp,db}}^{\mathrm{energy\ only}}}{10^6} \tag{AIII-46}$$

$$\mathrm{E\_I\_ENERGY}_{\mathrm{y,i,l,dp,db}} = \frac{\overline{\mathrm{demand\_by\_agent}}_{\mathrm{y,i,l,dp,db}}\overline{\mathrm{dur}}_{\mathrm{l,gp,gb}}\overline{\mathrm{p}}_{\mathrm{y,l.dp,db}}^{\mathrm{energy\ only}}}{10^{6}} \tag{AIII-47}$$

$$\begin{aligned}&\mathrm{E\_EX\_ENERGY}_{\mathrm{y,l,dp,db}}\\ &\quad = \frac{\overline{\mathrm{demand\_by\_agent}}_{\mathrm{y,ex,l,dp,db}}\overline{\mathrm{dur}}_{\mathrm{l,gp,gb}}\overline{\mathrm{p}}_{\mathrm{y,l.dp,db}}^{\mathrm{energy\ only}}P\_EXP\_ADJ_{\mathrm{y,l.dp,db}}}{10^{6}}\end{aligned} \tag{AIII-48}$$

TD&O electricity demand:

$$\begin{aligned}&\mathrm{E\_II\_EE\_TDeO}_{\mathrm{y,l,dp,db}}\\ &\quad = \mathrm{LOSS}_{\mathrm{y,l,p,b}}\left(\sum_{\mathrm{t,f}}\overline{\mathrm{pgen}}_{\mathrm{y,t,f,l,p,b}} + \overline{\mathrm{pimp}}_{\mathrm{y,l,p,b}} + \overline{\mathrm{pexp}}_{\mathrm{y,l,p,b}}\right.\\ &\quad \left. - \overline{\mathrm{ppumped}}_{\mathrm{y,l,p,b}}\right)\overline{\mathrm{dur}}_{\mathrm{l,dp,db}}\frac{\overline{\mathrm{p}}_{\mathrm{y,l.dp,db}}^{\mathrm{energy\ only}}}{10^{6}}\end{aligned} \tag{AIII-49}$$

Generation equilibrium between receipts and expenditures:

$$\begin{aligned}&\sum_{\mathrm{sne}}\mathrm{E\_II\_EQ\_ENERGY}_{\mathrm{y,sne,l,p,b}} + \mathrm{E\_II\_EE\_TDeO}_{\mathrm{y,l,p,b}} + \sum_{\mathrm{gp,gb,t}}\mathrm{E\_II\_EE\_GEN}_{\mathrm{y,l,p,b,gp,gb,t}}\\ &\quad + \sum_{\mathrm{i}}\mathrm{E\_I\_ENERGY}_{\mathrm{y,i,l,p,b}} + \mathrm{E\_EX\_ENERGY}_{\mathrm{y,l,p,b}}\\ &\quad = \sum_{\mathrm{gne,t}}\mathrm{E\_II\_QE\_GEN}_{\mathrm{y,gne,l,p,b,t}} + \sum_{\mathrm{dp,db,t}}\mathrm{E\_II\_EE\_GEN}_{\mathrm{y,l,dp,db,p,b,t}}\\ &\quad + \sum_{\mathrm{pf,t}}\mathrm{E\_F\_E\_GEN}_{\mathrm{y,pf,l,p,b,t}} + \sum_{\mathrm{tx,t}}\mathrm{E\_TAX\_E\_GEN}_{\mathrm{y,tx,l,p,b,t}}\\ &\quad + \mathrm{E\_M\_E\_GEN}_{\mathrm{y,l,p,b}} + \mathrm{TOTAL\_SURPLUS}_{\mathrm{y,l,p,b}}\\ &\quad + \overline{\mathrm{rights}}_{\mathrm{y,l,t}}^{\mathrm{CO2}}\overline{\mathrm{p}}_{\mathrm{y}}^{\mathrm{CO2}}\left(\frac{\overline{\mathrm{pgen}}_{\mathrm{y,t,f,l,p,b}}\,\overline{\mathrm{co2}}_{\mathrm{t,f}}^{\mathrm{fuel\_content}}\,\overline{\mathrm{dur}}_{\mathrm{l,p,b}}}{\sum_{t`,f`,l`,p`,b`}\left(\overline{\mathrm{pgen}}_{\mathrm{y,t`,f`,l`,p`,b`}}\,\overline{\mathrm{co2}}_{\mathrm{t`,f`}}^{\mathrm{fuel\_content}}\,\overline{\mathrm{dur}}_{\mathrm{l`,p`,b`}}\right)}\right)\end{aligned} \tag{AIII-50}$$

TD&O equilibrium between receipts and expenditures:

$$\begin{aligned}&\sum_{gne}\mathrm{E\_II\_QE\_TDeO}_{\mathrm{y,gne}} + \sum_{l,dp,db}\mathrm{E\_II\_E\_TDeO}_{\mathrm{y,l,dp,db}} + \sum_{pf}\mathrm{E\_F\_E\_TDeO}_{\mathrm{y,pf}}\\ &\quad + \sum_{tx}\mathrm{E\_TAX\_E\_TDeO}_{\mathrm{y,tx}} + \mathrm{E\_M\_E\_TDeO}_{\mathrm{y}}\\ &\quad = \sum_{sne}\mathrm{E\_II\_EQ\_POWER}_{\mathrm{y,sne}} + \sum_{i}\mathrm{E\_I\_POWER}_{\mathrm{y,i}} + \mathrm{E\_EX\_POWER}_{\mathrm{y}}\end{aligned} \tag{AIII-51}$$

Annex IV The Electricity Power Generation Operation and Expansion Planning Model

The BU model used on this thesis is a hydrothermal generation operation and expansion model developed under two formulations.

The first one is a linear optimization formulation (AIV.2). The model minimizes the total generation costs – fuel, operation and maintenance, emissions and installed capacity amortization costs – while respecting the electricity generation technologies technical constraints – production capacity, thermodynamic efficiency, water inflow, reservoir capacity, pumping efficiency – and the system constraints – necessity for firm reserve requirements and demand balance.

The wind production availability is corrected by a historic wind profile to reproduce the intermittent limitations of the technology. This simple representation is very limiting under higher wind penetration levels and it is incapable of correct handling possible wind spillovers. However, the simpler representation is more than capable under the base year used by this thesis and the limited years range simulated. It is recommended that any further research that deals with a more actual base year and a bigger wind penetration to revise this formulation.

Hydroelectric water reservoir management is carried between the time periods defined by the load block disaggregation. The periods used on this thesis represents usually months, either grouped in chronological seasons or represented individually.

The BU linear model sets, parameters and equations can be found bellow (AIV.1) while the GAMS code and all technological parameters values used by this thesis are publicly available in the website: www.renatorodrigues.info

The second model formulation presented in this Annex is of non-linear formulation. The model represents the equivalent electricity mixed complementarity conditions of the linear model firstly presented.

In order to easy the understanding, we firstly describe the equivalent Lagrangean problem (AIV.3) and, only after, we present the derived mixed complementary equations derived from the KKT stationary, feasibility and complementarity conditions of the previous model.

The mixed complementarity model obtained from the KKT conditions (AIV.4) is directly used on the H-GEMED model formulation and it is perfectly equivalent to the original BU linear model formulated.

AIV.1 Sets, parameters and variables

Sets:

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)
f	Fuel (Enriched_Uranium, Coal, Natural_Gas, Fuel-oil)
p	Period (year, season or month)
b	Load block (group of hours inside each period)

Variables:

$\text{PGEN}_{y,t,f,l,p,b}$	Electricity power generation by each technology (MW)
$\text{PPUMPED}_{y,l,p,b}$	Pumping consumed electricity power (MW)
$\text{RES}_{y,l,p}$	Hydro technology reservoir level (MW)
$\text{TCAP}_{y,l,t}$	Total installed capacity potency
$\text{PINS}_{y,l,t}$	New installed capacity by year

Parameters:

$\overline{\text{oem\_vom}}_{y,t}$	operation and maintenance variable costs (€/MWh)
$\overline{\text{oem\_fom}}_{y,l,t}^{labor}$	operation and maintenance labor fixed costs (€/KW)
$\overline{\text{oem\_fom}}_{y,l,t}^{sc}$	operation and maintenance social contribution fixed costs fixed costs (€/KW)
$\overline{\text{oem\_fom}}_{y,l,t}^{equip}$	operation and maintenance equipment fixed costs (€/KW)
$\bar{\eta}_{y,l,t}$	Thermodynamic efficiency (Enriched uranium: MWh/kg, coal: MWh/t, gas natural: MWh/10^3 m^3, fuel-oil: MWh/t)
$\overline{\text{own\_cons}}$	Initial own consumption of electricity by the generation activity (%)
$\overline{\text{overn\_costs}}_{y,t}$	Overnight new capacity investment costs (€/KW)
$\overline{\text{loss}}_{y,l,p,b}$	Transmission and distributions losses proportion
$\overline{\text{dur}}_{l,p,b}$	load block duration (hours)
$\overline{\text{cap}}_{y,l,t}$	power plant technology existent installed capacity (MW)
$\overline{\text{cap}}_{y,l,t}^{to\_be\_amort}$	power plant technology existent installed capacity not amortized (including exclusion of installed capacity previous liberalization, 1997, considered already paid as stranded costs) (MW)
$\bar{p}_{y,p,t,f}^{fuel}$	fuel price: enriched uranium (€/Kg), coal (€/t), gas natural (€/miles m3) and fuel-oil (€/t diesel)

$\overline{\text{demand}}_{y,l,p,b}$	electricity power demanded (households, non-electricity sectors and exports) (MW)
$\overline{\text{pctg}}_{y,l}^{\text{foil\_on\_fg}}$	Percentage of fuel-oil combustible used on Fuel-Gas technology (%)
$\overline{\text{pgen\_base\_year}}_{l,p,b,t}$	Generated potency in the base year (MW)
$\overline{\text{pimp}}_{y,l,p,b}$	Generated potency imported (MW)
$\overline{\text{pexp}}_{y,l,p,b}$	Generated potency exported (MW)
$\overline{\text{inflows}}_{y,l,p}$	hydroelectric reservoir inflows (MW)
$\overline{\text{ror\_inflows}}_{y,l,p}$	hydroelectric run of river inflows (MW)
$\overline{\text{eff}}^{\text{Pump}}$	Pumping technologies efficiency (%)
$\overline{\text{res\_max}}_{y,l,t}$	maximum reservoir level (MWh)
$\overline{\text{availability}}_{y,l,t}$	average availability of technology (%)
$\overline{\text{premium}}_{t,f}^{\text{renew}}$	technology renewable premium (€/MWh)
$\overline{\text{rights}}_{y,l,t}^{\text{CO2}}$	technology emission rights given by the government (MMtCO2e)
$\overline{\text{co2}}_{t,f}^{\text{fuel\_content}}$	co2 emission potential by combustible (MMtCO2e/ MWh)
$\bar{p}_{y}^{\text{CO2}}$	co2 price (€/tCO2)
$\overline{\text{non\_intt\_coverage}}$	Capacity reserve required in non-intermittent generation technologies for the higher demanding load block
$\overline{\text{idc}}_{t}$	accumulated interest during construction
$\overline{\text{crf}}_{t}$	Capital recovery factor, i.e., accumulated discount payments during amortization

AIV.2 The linear Electricity Power Generation Operation and Expansion Planning Model

Min:

$$
\begin{aligned}
&\sum_{t,f,p,b} \overbrace{\frac{\mathrm{PGEN}_{y,t,f,l,p,b}\,\overline{\eta}_{y,l,t}\,\overline{p}^{\mathrm{fuel}}_{y,p,t,f}\,\overline{\mathrm{dur}}_{l,p,b}}{10^6}}^{\text{Fuel cost}} \\
&+\sum_{t,f,p,b} \overbrace{\frac{\mathrm{PGEN}_{y,t,f,l,p,b}\,\overline{\mathrm{co2}}^{\mathrm{fuel\_content}}_{t,f}\,\overline{p}^{\mathrm{CO2}}_{y}\overline{\mathrm{dur}}_{l,p,b}}{10^6}}^{\text{CO}_2\text{ emission costs}} \\
&+\sum_{t,f,p,b} \overbrace{\frac{\mathrm{PGEN}_{y,t,f,l,p,b}\overline{\mathrm{oem\_vom}}_{y,t}\overline{\mathrm{dur}}_{l,p,b}}{10^6}}^{\text{Variable O\&}M\text{ equipament costs}} \\
&-\sum_{t,f,p,b} \overbrace{\frac{\mathrm{PGEN}_{y,t,f,l,p,b}\overline{\mathrm{premium}}^{\mathrm{renew}}_{t,f}\overline{\mathrm{dur}}_{l,p,b}}{10^6}}^{\text{Renewable premiun income}} \\
&+\sum_{t} \overbrace{\frac{\left(\overline{\mathrm{oem\_fom}}^{\mathrm{labor}}_{y,l,t}+\overline{\mathrm{oem\_fom}}^{\mathrm{sc}}_{y,l,t}+\overline{\mathrm{oem\_fom}}^{\mathrm{equip}}_{y,l,t}\right)\mathrm{TCAP}_{y,l,t}}{10^3}}^{\text{Fixed O\&}M\text{ costs}} \\
&+\sum_{t} \overbrace{\frac{\overline{\mathrm{overn\_costs}}_{y,t}\overline{\mathrm{idc}}_{t}\overline{\mathrm{crf}}_{t}\left(\overline{\mathrm{cap}}^{\mathrm{to\_be\_amort}}_{y,l,t}+\sum_{\substack{y'\le y\\ y`\ge y-l\_t}}\mathrm{PINS}_{y',l,t}\right)}{10^3}}^{\text{Installed capacity amortization costs paid in the year}} \\
&-\sum_{t,f,p,b} \overbrace{\overline{\mathrm{rights}}^{\mathrm{CO2}}_{y,l,t}\,\overline{p}^{\mathrm{CO2}}_{y}}^{\text{Emission rights}} \qquad \forall y,l
\end{aligned}
\tag{AIV.2-1}
$$

Subject to:

Demand balance:

$$
\begin{aligned}
\overline{\mathrm{demand}}_{y,l,p,b} \le{}& \sum_{t,f}\mathrm{PGEN}_{y,t,f,l,p,b}+\overline{\mathrm{pimp}}_{y,l,p,b}-\mathrm{PPUMPED}_{y,l,p,b} \\
&-\left(\overline{\mathrm{own\_cons}}\right)\sum_{t,f}\mathrm{PGEN}_{y,t,f,l,p,b} \\
&-\overline{\mathrm{loss}}_{y,l,p,b}\left(\sum_{t,f}\mathrm{PGEN}_{y,t,f,l,p,b}+\overline{\mathrm{pimp}}_{y,l,p,b}+\overline{\mathrm{pexp}}_{y,l,p,b}\right. \\
&\left.-\mathrm{PPUMPED}_{y,l,p,b}\right)
\end{aligned}
\tag{AIV.2-2}
$$

Hydro reservoir management level:

$$
\overline{\mathrm{inflows}}_{y,l,p} \ge \sum_{b}\mathrm{PGEN}_{y,\mathrm{Hyd\_Res},na,l,p,b}\overline{\mathrm{dur}}_{l,p,b}-\mathrm{RES}_{y,l,p}+\mathrm{RES}_{y,l,p+1}
\tag{AIV.2-3}
$$

Hydro run of river production:

$$
\mathrm{PGEN}_{y,\mathrm{Hyd\_RoR},na,l,p,b}\overline{\mathrm{dur}}_{l,p,b} \le \overline{\mathrm{ror\_inflows}}_{y,l,p}
\tag{AIV.2-4}
$$

Pumping efficiency:

$$\sum_{p,b} \mathrm{PPUMPED}_{y,l,p,b}\overline{\mathrm{dur}}_{l,p,b}\overline{\mathrm{eff}}^{\mathrm{Pump}} \geq \sum_{p,b} \mathrm{PGEN}_{y,\mathrm{Pump},na,l,p,b}\overline{\mathrm{dur}}_{l,p,b} \qquad \text{AIV.2-5}$$

Maximum pumping capacity:

$$\sum_{p,b} \mathrm{PGEN}_{y,\mathrm{Pump},na,l,p,b}\overline{\mathrm{dur}}_{l,p,b} \leq \overline{\mathrm{res\_max}}_{y,l,\mathrm{Pump}} \qquad \text{AIV.2-6}$$

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

$$\mathrm{PGEN}_{y,F-G,\mathrm{Fuel-oil},l,p,b} = \overline{\mathrm{pctg}}_{y,l}^{\mathrm{foil\_on\_fg}} \sum_{f} \mathrm{PGEN}_{y,F-G,f,l,p,b} \qquad \text{AIV.2-7}$$

Wind power production at each load block:

$$\mathrm{PGEN}_{y,\mathrm{Wind},na,l,p,b} = \overline{\mathrm{pgen\_base\_year}}_{l,p,b,\mathrm{Wind}} \frac{\mathrm{TCAP}_{y,l,\mathrm{Wind}}}{\overline{\mathrm{cap}}_{\mathrm{Base\ year},l,\mathrm{Wind}}} \qquad \text{AIV.2-8}$$

Other special regime renewable production at each load block:

$$\mathrm{PGEN}_{y,\mathrm{ORSR},na,l,p,b} = \overline{\mathrm{pgen\_base\_year}}_{l,p,b,\mathrm{ORSR}} \frac{\mathrm{TCAP}_{y,l,\mathrm{ORSR}}}{\overline{\mathrm{cap}}_{\mathrm{Base\ year},l,\mathrm{ORSR}}} \qquad \text{AIV.2-9}$$

Maximum production capacity:

$$\mathrm{PGEN}_{y,t,f,l,p,b} \leq \overline{\mathrm{availability}}_{y,l,t}\mathrm{TCAP}_{y,l,t} \qquad \text{AIV.2-10}$$

Maximum hydro reservoir capacity:

$$\mathrm{RES}_{y,l,p} \leq \overline{\mathrm{res\_max}}_{y,l,\mathrm{Hyd}} \qquad \text{AIV.2-11}$$

Total installed capacity:

$$\mathrm{TCAP}_{y,l,t} = \overline{\mathrm{cap}}_{y,l,t} + \sum_{\substack{y' \leq y \\ y' \geq y-\mathrm{life\_time}}} \mathrm{PINS}_{y',l,t} \qquad \text{AIV.2-12}$$

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

$$\sum_{\mathrm{t\_non\_intt}} \mathrm{TCAP}_{y,l,t} \geq \overline{\mathrm{non\_intt\_coverage}} \max_{p,b}\left(\overline{\mathrm{demand}}_{y,l,p,b}\right) \qquad \text{AIV.2-13}$$

AIV.3 The equivalent Lagrangean problem

Additional Variables:

λ, μ Dual variables

The equivalent Lagrangean problem is given by:

$MINIMIZE$:

$$
\begin{aligned}
&\mathcal{L}\left(\mathrm{PGEN}_{y,t,f,l,p,b}, \mathrm{PPUMPED}_{y,l,p,b}, \mathrm{RES}_{y,l,p}, \mathrm{TCAP}_{y,l,t}, \mathrm{PINS}_{y,l,t}, \lambda, \mu\right) = \\
&\sum_{y,l,t,f,p,b} \overbrace{\frac{\mathrm{PGEN}_{y,t,f,l,p,b}\ \overline{\eta}_{y,l,t}\ \overline{\mathrm{p}}^{\mathrm{fuel}}_{y,p,t,f}\ \overline{\mathrm{dur}}_{l,p,b}}{10^6}}^{\text{Fuel cost}} + \sum_{y,l,t,f,p,b} \overbrace{\frac{\mathrm{PGEN}_{y,t,f,l,p,b}\ \overline{\mathrm{co2}}^{\mathrm{fuel\_content}}_{t,f}\ \overline{\mathrm{p}}^{\mathrm{CO2}}_{y}\overline{\mathrm{dur}}_{l,p,b}}{10^6}}^{\text{CO}_2\text{ emission costs}} \\
&+ \sum_{y,l,t,f,p,b} \overbrace{\frac{\mathrm{PGEN}_{y,t,f,l,p,b}\overline{\mathrm{oem\_vom}}_{y,t}\overline{\mathrm{dur}}_{l,p,b}}{10^6}}^{\text{Variable O\&}M\text{ equipament costs}} - \sum_{y,l,t,f,p,b} \overbrace{\frac{\mathrm{PGEN}_{y,t,f,l,p,b}\overline{\mathrm{premium}}^{\mathrm{renew}}_{t,f}\overline{\mathrm{dur}}_{l,p,b}}{10^6}}^{\text{Renewable premiun income}} \\
&+ \sum_{y,l,t} \overbrace{\frac{\left(\overline{\mathrm{oem\_fom}}^{\mathrm{labor}}_{y,l,t} + \overline{\mathrm{oem\_fom}}^{\mathrm{sc}}_{y,l,t} + \overline{\mathrm{oem\_fom}}^{\mathrm{equip}}_{y,l,t}\right)\mathrm{TCAP}_{y,l,t}}{10^3}}^{\text{Fixed O\&}M\text{ costs}} \\
&+ \sum_{y,l,t} \overbrace{\frac{\overline{\mathrm{overn\_costs}}_{y,t}\overline{\mathrm{idc}}_{t}\overline{\mathrm{crf}}_{t}\left(\overline{\mathrm{cap}}^{\mathrm{to\_be\_amort}}_{y,l,t} + \sum_{\substack{y'\leq y \\ y`\geq y-l_t}} \mathrm{PINS}_{y',l,t}\right)}{10^3}}^{\text{Installed capacity amortization costs paid in the year}} \\
&- \sum_{y,l,t,f,p,b} \overbrace{\overline{\mathrm{rights}}^{\mathrm{CO2}}_{y,l,t}\overline{\mathrm{p}}^{\mathrm{CO2}}_{y}}^{\text{Emission rights}} \\
&- \sum_{y,l,p,b} \lambda^{Dem}_{y,l,p,b}\Bigg[\overline{\mathrm{demand}}_{y,l,p,b} - \left(\sum_{t,f}\mathrm{PGEN}_{y,t,f,l,p,b}\right) - \overline{\mathrm{pimp}}_{y,l,p,b} + \mathrm{PPUMPED}_{y,l,p,b} \\
&\qquad + \left(\overline{\mathrm{own\_cons}}\right)\left(\sum_{t,f}\mathrm{PGEN}_{y,t,f,l,p,b}\right) \\
&\qquad + \overline{\mathrm{loss}}_{y,l,p,b}\Bigg(\left(\sum_{t,f}\mathrm{PGEN}_{y,t,f,l,p,b}\right) + \overline{\mathrm{pimp}}_{y,l,p,b} + \overline{\mathrm{pexp}}_{y,l,p,b} \\
&\qquad - \mathrm{PPUMPED}_{y,l,p,b}\Bigg)\Bigg] \\
&- \sum_{y,l,p} \lambda^{Hyd\_res}_{y,l,p}\left[\left(\sum_{b}\mathrm{PGEN}_{y,Hyd\_res,na,l,p,b}\overline{\mathrm{dur}}_{l,p,b}\right) - \mathrm{RES}_{y,l,p} + \mathrm{RES}_{y,l,p+1} - \overline{\mathrm{inflows}}_{y,l,p}\right] \\
&- \sum_{y,l,p} \lambda^{Hyd\_RoR}_{y,l,p}\left[\mathrm{PGEN}_{y,Hyd\_RoR,na,l,p,b} - \frac{\overline{\mathrm{ror\_inflows}}_{y,l,p}}{\sum_{b`}\overline{\mathrm{dur}}_{l,p,b`}}\right] \\
&- \sum_{y,l,p} \lambda^{Pump\_eff}_{y,l,p}\left[\sum_{b}\left(\mathrm{PGEN}_{y,Pump,na,l,p,b}\overline{\mathrm{dur}}_{l,p,b} - \mathrm{PPUMPED}_{y,l,p,b}\overline{\mathrm{dur}}_{l,p,b}\overline{\mathrm{eff}}^{\mathrm{Pump}}\right)\right]
\end{aligned}
\tag{AIV.3-1}
$$

$$
\begin{aligned}
&-\sum_{y,l,p}\lambda_{y,l,p}^{Pump\_Max}\left[\sum_{\mathrm{b}}\left(\mathrm{PGEN}_{\mathrm{y,Pump,na,l,p,b}}\overline{\mathrm{dur}}_{\mathrm{l,p,b}}\right)-\overline{\mathrm{res\_max}}_{\mathrm{y,l,Pump}}\right]\\
&-\sum_{y,l}\lambda_{y,l}^{Reserves}\left[\overline{\mathrm{non\_ıntt\_coverage}}\max_{\mathrm{p,b}}\left(\overline{\mathrm{demand}}_{\mathrm{y,l,p,b}}\right)-\sum_{\mathrm{t_{non_{intt}}}}\mathrm{TCAP}_{\mathrm{y,l,t}}\right]\\
&-\sum_{y,t,f,l,p,b}\lambda_{\mathrm{y,t,f,l,p,b}}^{Cap\_availability}\big[\mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}}\\
&\qquad\qquad-\overline{\mathrm{stochastıc\_adȷ\_term}}_{\mathrm{y,l,p,b}}\overline{\mathrm{avaılabılıty}}_{\mathrm{y,l,t}}\mathrm{TCAP}_{\mathrm{y,l,t}}\big]\\
&-\sum_{\mathrm{y,l,p}}\lambda_{\mathrm{y,l,p}}^{Hyd\_res\_Max}\left[\mathrm{RES}_{\mathrm{y,l,p}}-\overline{\mathrm{res\_max}}_{\mathrm{y,l,Hyd}}\right]\\
&-\sum_{y,l,p,b}\mu_{y,l,p,b}^{F-G\_Fuel-Oil_{use}}\left[\mathrm{PGEN}_{\mathrm{y,F-G,Fuel-oil,l,p,b}}-\overline{\mathrm{pctg}}_{\mathrm{y,l}}^{\mathrm{foil\_on\_fg}}\left(\sum_{\mathrm{f}}\mathrm{PGEN}_{\mathrm{y,F-G,f,l,p,b}}\right)\right]\\
&-\sum_{y,l,p,b}\mu_{y,l,p,b}^{F-G\_Gas_{use}}\left[\mathrm{PGEN}_{\mathrm{y,F-G,Gas,l,p,b}}-\left(1-\overline{\mathrm{pctg}}_{\mathrm{y,l}}^{\mathrm{foil\_on\_fg}}\right)\left(\sum_{\mathrm{f}}\mathrm{PGEN}_{\mathrm{y,F-G,f,l,p,b}}\right)\right]\\
&-\sum_{y,l,p,b}\mu_{y,l,p,b}^{Wind}\left[\mathrm{PGEN}_{\mathrm{y,Wind,na,l,p,b}}-\overline{\mathrm{pgen\_base\_year}}_{\mathrm{l,p,b,Wind}}\left(\frac{\mathrm{TCAP}_{\mathrm{y,l,Wind}}}{\overline{\mathrm{cap}}_{\mathrm{Base\ year,l,Wind}}}\right)\right]\\
&-\sum_{y,l,p,b}\mu_{y,l,p,b}^{ORSR}\left[\mathrm{PGEN}_{\mathrm{y,ORSR,na,l,p,b}}-\overline{\mathrm{pgen\_base\_year}}_{\mathrm{l,p,b,ORSR}}\left(\frac{\mathrm{TCAP}_{\mathrm{y,l,ORSR}}}{\overline{\mathrm{cap}}_{\mathrm{Base\ year,l,ORSR}}}\right)\right]\\
&-\sum_{y,l,t}\mu_{y,l,t}^{TCap}\left[\mathrm{TCAP}_{\mathrm{y,l,t}}-\overline{\mathrm{cap}}_{\mathrm{y,l,t}}-\sum_{\substack{\mathrm{y'\le y}\\ \mathrm{y`\ge y-life\_time}}}\mathrm{PINS}_{\mathrm{y',l,t}}\right]
\end{aligned}
$$

AIV.4 The equivalent electricity mixed complementarity model

The stationary conditions of the equivalent KKT problem are given by:

$$
\begin{aligned}
&\frac{\partial\mathcal{L}_s\left(\mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}},\mathrm{PPUMPED}_{\mathrm{y,l,p,b}},\mathrm{RES}_{\mathrm{y,l,p}},\mathrm{TCAP}_{\mathrm{y,l,t}},\mathrm{PINS}_{\mathrm{y,l,t}},\lambda,\mu\right)}{\partial\mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}}}=\\
&\left[\frac{\bar{\mathrm{\eta}}_{\mathrm{y,l,t}}\,\bar{\mathrm{p}}_{\mathrm{y,p,t,f}}^{\mathrm{fuel}}\,\overline{\mathrm{dur}}_{\mathrm{l,p,b}}}{10^6}+\frac{\overline{\mathrm{co2}}_{\mathrm{t,f}}^{\mathrm{fuel\_content}}\,\bar{\mathrm{p}}_{\mathrm{y}}^{\mathrm{CO2}}\overline{\mathrm{dur}}_{\mathrm{l,p,b}}}{10^6}+\frac{\overline{\mathrm{oem\_vom}}_{\mathrm{y,t}}\overline{\mathrm{dur}}_{\mathrm{l,p,b}}}{10^6}\right.\\
&\qquad\qquad\left.-\frac{\overline{\mathrm{premıum}}_{\mathrm{t,f}}^{\mathrm{renew}}\overline{\mathrm{dur}}_{\mathrm{l,p,b}}}{10^6}\right]\\
&-\lambda_{y,l,p,b}^{Dem}\left[-1+(\overline{\mathrm{own\_cons}})+\overline{\mathrm{loss}}_{\mathrm{y,l,p,b}}\right]\\
&-\left\{\lambda_{y,l,p}^{Hyd\_Res}\left[\overline{\mathrm{dur}}_{\mathrm{l,p,b}}\right]\right\}_{if\ t=Hyd\_Res,f=\mathrm{na}}\\
&-\left\{\lambda_{y,l,p}^{Pump\_eff}\left[\overline{\mathrm{dur}}_{\mathrm{l,p,b}}\right]\right\}_{if\ t=Pump,f=\text{"}na\text{"}}\\
&-\left\{\lambda_{y,l,p}^{Pump\_Max}\left[\overline{\mathrm{dur}}_{\mathrm{l,p,b}}\right]\right\}_{if\ t=Pump,f=\text{"}na\text{"}}\\
&-\left\{\lambda_{y,l,p}^{Hyd\_RoR}[1]\right\}_{if\ t=Hyd\_RoR,f=\mathrm{na}}\\
&-\lambda_{\mathrm{y,t,f,l,p,b}}^{Cap\_availability}[1]\\
&-\left\{\mu_{y,l,p,b}^{F-G\_Fuel-Oil\_use}\left[1-\overline{\mathrm{pctg}}_{\mathrm{y,l}}^{\mathrm{foil\_on\_fg}}\right]\right\}_{if\ t=F-G,f=Fuel-oil}\\
&-\left\{\mu_{y,l,p,b}^{F-G\_Gas\_use}\left[\overline{\mathrm{pctg}}_{\mathrm{y,l}}^{\mathrm{foil\_on\_fg}}\right]\right\}_{if\ t=F-G,f=Natural\_gas}
\end{aligned}
\tag{AIV.4-1}
$$

$$-\left\{\mu_{y,l,p,b}^{Wind}[1]\right\}_{if\ t=Wind,f="na"}$$
$$-\left\{\mu_{y,l,p,b}^{ORSR}[1]\right\}_{if\ t=ORSR,f="na"}=0$$

$$\frac{\partial\mathcal{L}_s\left(\mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}},\mathrm{PPUMPED}_{\mathrm{y,l,p,b}},\mathrm{RES}_{\mathrm{y,l,p}},\mathrm{TCAP}_{\mathrm{y,l,t}},\mathrm{PINS}_{\mathrm{y,l,t}},\lambda,\mu\right)}{\partial\mathrm{PPUMPED}_{\mathrm{y,l,p,b}}} = -\lambda_{y,l,p,b}^{Dem}\left[1-\overline{\mathrm{loss}}_{\mathrm{y,l,p,b}}\right]-\lambda_{y,l,p}^{Pump\_eff}\left[-\overline{\mathrm{dur}}_{\mathrm{l,p,b}}\overline{\mathrm{eff}}^{\mathrm{Pump}}\right]=0 \tag{AIV.4-2}$$

$$\frac{\partial\mathcal{L}_s\left(\mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}},\mathrm{PPUMPED}_{\mathrm{y,l,p,b}},\mathrm{RES}_{\mathrm{y,l,p}},\mathrm{TCAP}_{\mathrm{y,l,t}},\mathrm{PINS}_{\mathrm{y,l,t}},\lambda,\mu\right)}{\partial\mathrm{RES}_{\mathrm{y,l,p}}} = -\lambda_{y,l,p}^{Hyd_{Res}}[-1]-\lambda_{y,l,p-1}^{Hyd_{Res}}[+1]-\lambda_{\mathrm{y,l,p}}^{Hyd\_res\_Max}=0 \tag{AIV.4-3}$$

$$\begin{aligned}
&\frac{\partial\mathcal{L}_s\left(\mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}},\mathrm{PPUMPED}_{\mathrm{y,l,p,b}},\mathrm{RES}_{\mathrm{y,l,p}},\mathrm{TCAP}_{\mathrm{y,l,t}},\mathrm{PINS}_{\mathrm{y,l,t}},\lambda,\mu\right)}{\partial\mathrm{TCAP}_{\mathrm{y,l,t}}}\\
&\quad=\left[\frac{\left(\overline{\mathrm{oem\_fom}}_{\mathrm{y,l,t}}^{\mathrm{labor}}+\overline{\mathrm{oem\_fom}}_{\mathrm{y,l,t}}^{\mathrm{sc}}+\overline{\mathrm{oem\_fom}}_{\mathrm{y,l,t}}^{\mathrm{equip}}\right)}{10^3}\right]\\
&\quad-\left\{\lambda_{y,l}^{Reserves}[-1]\right\}_{if\ t=non\ intermitent\ technology}\\
&\quad-\left\{\mu_{y,l,p,b}^{Wind}\left[-\left(\frac{\overline{\mathrm{pgen\_base\_year}}_{\mathrm{l,p,b,Wind}}}{\overline{\mathrm{cap}}_{\mathrm{Base\ year,l,Wind}}}\right)\right]\right\}_{if\ t=Wind}\\
&\quad-\left\{\mu_{y,l,p,b}^{ORSR}\left[-\left(\frac{\overline{\mathrm{pgen\_base\_year}}_{\mathrm{l,p,b,ORSR}}}{\overline{\mathrm{cap}}_{\mathrm{Base\ year,l,ORSR}}}\right)\right]\right\}_{if\ t=ORSR}-\mu_{y,l,t}^{TCap}[1]\\
&\quad-\lambda_{\mathrm{y,t,f,l,p,b}}^{Cap\_availability}\left[-\overline{\mathrm{availability}}_{\mathrm{y,l,t}}\overline{\mathrm{stochastic\_adj\_term}}_{\mathrm{y,l,p,b,y}}\right]=0
\end{aligned} \tag{AIV.4-4}$$

$$\frac{\partial\mathcal{L}_s\left(\mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}},\mathrm{PPUMPED}_{\mathrm{y,l,p,b}},\mathrm{RES}_{\mathrm{y,l,p}},\mathrm{TCAP}_{\mathrm{y,l,t}},\mathrm{PINS}_{\mathrm{y,l,t}},\lambda,\mu\right)}{\partial\mathrm{PINS}_{\mathrm{y,l,t}}} =\left[\sum_{\substack{\mathrm{y'>y}\\ \mathrm{y'<y+life\_time}}}\frac{\overline{\mathrm{overn\_costs}}_{\mathrm{y,t}}\overline{\mathrm{idc}}_{\mathrm{t}}\overline{\mathrm{crf}}_{\mathrm{t}}}{10^3}\right]-\mu_{y,l,t}^{TCap}[-1]=0 \tag{AIV.4-5}$$

The feasibility and complementarity conditions to equality and inequality constraints are:

$$\begin{aligned}
&\overline{\mathrm{demand}}_{\mathrm{y,l,p,b}}-\sum_{\mathrm{t,f}}\mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}}-\overline{\mathrm{pimp}}_{\mathrm{y,l,p,b}}+\mathrm{PPUMPED}_{\mathrm{y,l,p,b}}\\
&\quad+\left(\overline{\mathrm{own}}_{\mathrm{cons}}\right)\sum_{\mathrm{t,f}}\mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}}\\
&\quad+\overline{\mathrm{loss}}_{\mathrm{y,l,p,b}}\left(\sum_{\mathrm{t,f}}\mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}}+\overline{\mathrm{pimp}}_{\mathrm{y,l,p,b}}+\overline{\mathrm{pexp}}_{\mathrm{y,l,p,b}}\right.\\
&\quad\left.-\mathrm{PPUMPED}_{\mathrm{y,l,p,b}}\right)\leq 0\\
&\qquad\qquad\perp\quad\lambda_{y,l,p,b}^{Dem}\leq 0
\end{aligned} \tag{AIV.4-6}$$

$$\begin{aligned}
&\mathrm{TCAP}_{\mathrm{y,l,t}}-\overline{\mathrm{cap}}_{\mathrm{y,l,t}}-\sum_{\substack{\mathrm{y'\leq y}\\ \mathrm{y'\geq y-life_{time}}}}\mathrm{PINS}_{\mathrm{y',l,t}}=0\\
&\qquad\qquad\perp\quad\mu_{y,l,t}^{TCap}
\end{aligned} \tag{AIV.4-7}$$

$$\left(\sum_{\mathrm{b}} \mathrm{PGEN}_{\mathrm{y,Hyd\_Res,na,l,p,b}}\overline{\mathrm{dur}}_{\mathrm{l,p,b}}\right) - \mathrm{RES}_{\mathrm{y,l,p}} + \mathrm{RES}_{\mathrm{y,l,p+1}} - \overline{\mathrm{inflows}}_{\mathrm{y,l,p}} \leq 0 \qquad \perp \quad \lambda_{y,l,p}^{Hyd\_res} \leq 0 \tag{AIV.4-8}$$

$$\mathrm{PGEN}_{\mathrm{y,Hyd\_RoR,na,l,p,b}} - \frac{\overline{\mathrm{ror\_inflows}}_{\mathrm{y,l,p}}}{\sum_{b`} \overline{\mathrm{dur}}_{\mathrm{l,p,b`}}} \leq 0 \qquad \perp \quad \lambda_{y,l,p}^{Hyd\_RoR} \leq 0 \tag{AIV.4-9}$$

$$\sum_{b}\left(\mathrm{PGEN}_{\mathrm{y,Pump,na,l,p,b}}\overline{\mathrm{dur}}_{\mathrm{l,p,b}} - \mathrm{PPUMPED}_{\mathrm{y,l,p,b}}\overline{\mathrm{dur}}_{\mathrm{l,p,b}}\overline{\mathrm{eff}}^{\mathrm{Pump}}\right) \leq 0 \qquad \perp \quad \lambda_{y,l,p}^{Pump\_eff} \leq 0 \tag{AIV.4-10}$$

$$\sum_{\mathrm{b}}\left(\mathrm{PGEN}_{\mathrm{y,Pump,na,l,p,b}}\overline{\mathrm{dur}}_{\mathrm{l,p,b}}\right) - \overline{\mathrm{res\_max}}_{\mathrm{y,l,Pump}} \leq 0 \qquad \perp \quad \lambda_{y,l,p}^{Pump\_Max} \leq 0 \tag{AIV.4-11}$$

$$\mathrm{PGEN}_{\mathrm{y,F-G,Fuel-oil,l,p,b}} - \overline{\mathrm{pctg}}_{\mathrm{y,l}}^{\mathrm{foil_{on_{fg}}}} \sum_{\mathrm{f}} \mathrm{PGEN}_{\mathrm{y,F-G,f,l,p,b}} = 0 \qquad \perp \quad \mu_{y,l,p,b}^{F-G\_Fuel\_Oil\_use} \tag{AIV.4-12}$$

$$\mathrm{PGEN}_{\mathrm{y,F-G,Gas,l,p,b}} - \left(1 - \overline{\mathrm{pctg}}_{\mathrm{y,l}}^{\mathrm{foil_{on_{fg}}}}\right) \sum_{\mathrm{f}} \mathrm{PGEN}_{\mathrm{y,F-G,f,l,p,b}} = 0 \qquad \perp \quad \mu_{y,l,p,b}^{F-G\_Gas\_use} \tag{AIV.4-13}$$

$$\mathrm{PGEN}_{\mathrm{y,Wind,na,l,p,b}} - \overline{\mathrm{pgen_{base_{year}}}}_{\mathrm{l,p,b,Wind}} \frac{\mathrm{TCAP}_{\mathrm{y,l,Wind}}}{\overline{\mathrm{cap}}_{\mathrm{Base\ year,l,Wind}}} = 0 \qquad \perp \quad \mu_{y,l,p,b}^{Wind} \tag{AIV.4-14}$$

$$\mathrm{PGEN}_{\mathrm{y,ORSR,na,l,p,b}} - \overline{\mathrm{pgen_{base_{year}}}}_{\mathrm{l,p,b,ORSR}} \frac{\mathrm{TCAP}_{\mathrm{y,l,ORSR}}}{\overline{\mathrm{cap}}_{\mathrm{Base\ year,l,ORSR}}} = 0 \qquad \perp \quad \mu_{y,l,p,b}^{ORSR} \tag{AIV.4-15}$$

$$\mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}} - \overline{\mathrm{stochastic_{adj_{term}}}}_{\mathrm{y,l,p,b}}\overline{\mathrm{availability}}_{\mathrm{y,l,t}}\mathrm{TCAP}_{\mathrm{y,l,t}} \leq 0 \qquad \perp \quad \lambda_{y,l,t}^{Cap\_Availability} \leq 0 \tag{AIV.4-16}$$

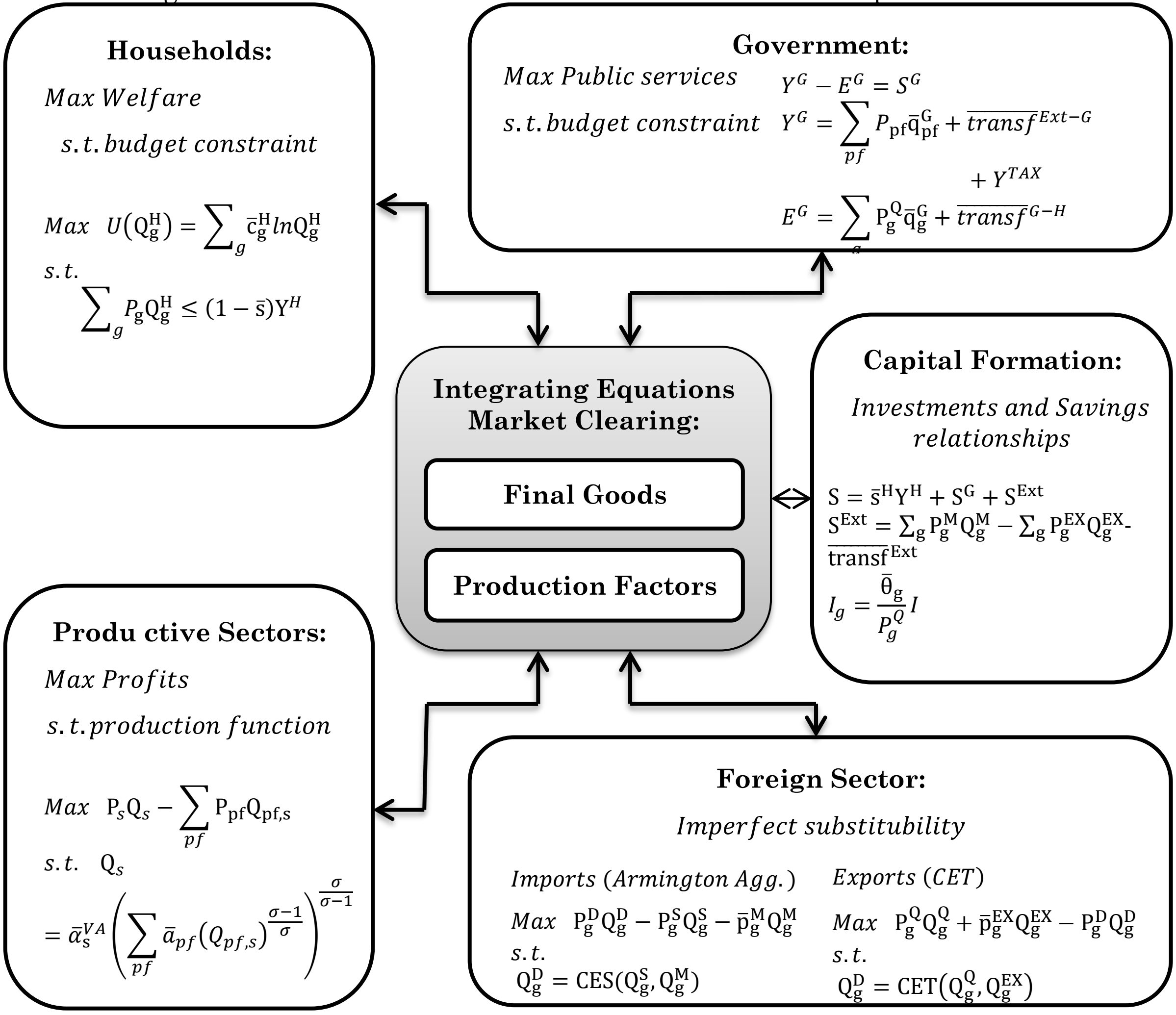
$$\mathrm{RES}_{\mathrm{y,l,p}} - \overline{\mathrm{res\_max}}_{\mathrm{y,l,Hyd}} \leq 0 \qquad \perp \quad \lambda_{\mathrm{y,l,p}}^{Hyd\_res\_Max} \leq 0 \tag{AIV.4-17}$$

$$\overline{\mathrm{non_{intt_{coverage}}}} \max_{\mathrm{p,b}}\left(\overline{\mathrm{demand}}_{\mathrm{y,l,p,b}}\right) - \sum_{\mathrm{t\_non\_intt}} \mathrm{TCAP}_{\mathrm{y,l,t}} \leq 0 \qquad \perp \quad \lambda_{y,l}^{Reserves} \leq 0 \tag{AIV.4-18}$$

Annex V The GEMED Model

The GEMED model assumes two production factors, labor and capital, perfectly mobile across sectors and allocated according to a perfectly competitive factors' market. Figure 13 presents the general structure of the CGE model developed.

Figure 13. Schematic CGE model structure and main equations.



Source: own elaboration.

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)[66] 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, simplified to a monotonous Cobb-Douglas function transformation, for representing 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 fixed quantities for the government consumption. 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.

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[66] 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 chapter. More policy oriented works should consider a more exhaustive representation of production sectors according to the policy consequences to be evaluated.

All savings finance investment goods that are distributed 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 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.

AV.1 Sets, parameters and variables

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 (year, season or month)
b (db,gb)	Load block (group of hours inside each period)

Parameters:

	Household Behavior:
$\bar{q}^{H}_{ey,pf}$	Quantity of production factor pf initially owned by the representative household
$\bar{\mathrm{c}}^{\mathrm{H}}_{\mathrm{ey,gne}}$, $\bar{c}^{H\_TDeO}_{ey}$, $\bar{c}^{H\_GEN}_{ey,l,p,b}$	Representative household marginal propensity to consume good gne, TD&O or GEN
$\bar{\mathrm{s}}^{H}_{ey}$	Representative Household marginal propensity to save
$\overline{psc}^{H}_{ey}$	Proportion of annual social contribution payments reverted directly to households

Productive sector sne parameters:

$\bar{\alpha}_s^{VA}$	Productivity parameter of sector value added composite good production function
$\bar{\mathrm{a}}_{sne,pf}^{VA}$	Share parameter of product factor on value added composite good production function
$\bar{\sigma}_{sne}^{VA}$	Elasticity of substitution between productive factors of sector sne
$\bar{c}_{ey,gne,sne}^{II}$, $\bar{c}_{ey,sne}^{II\_TDeO\_sne}$, $\bar{c}_{ey,l,dp,db,sne}^{II\_GEN\_sne}$	Share parameter of intermediate composites inputs gne (or TD&O or GEN) on sne sector production function
$\bar{c}_{ey,sne}^{VA}$	Share parameter of value added composite input on sne sector production function
$\overline{emiss\ rate}_{ey,sne}^{CO2}$	CO2 emission rate of sectors belonging to the Emission Trading System (ETS)

Imports Armington Aggregation:

$\bar{\alpha}_{gne}^{D}$	Productivity parameter of Armington aggregated imported and domestic produced supply of good g
$\bar{\mathrm{a}}_{\mathrm{gne}}^{D}$	Share parameter of domestic produced supply on Armington aggregate
$\bar{\sigma}_{\mathrm{gne}}^{D}$	Elasticity of substitution between imported and domestic produced good g

Exports CET disaggregation:

$\bar{\beta}_{\mathrm{gne}}^{Q}$	Productivity parameter of CET export and domestically destined good g
$\bar{b}_{\mathrm{gne}}^{Q}$	Share parameter of CET domestically destined good g
$\bar{\sigma}_{\mathrm{gne}}^{Q}$	Elasticity of transformation between domestic and external destined supply

TD&O sector parameters:

$\bar{c}_{ey,pf}^{pf\_TDeO}$	Share parameter of the production factors on TD&O production function
$\bar{c}_{ey,gne}^{II_{gne\_TD\&O}}$, $\bar{c}_{ey}^{II\_TDeO\_TDeO}$, $\bar{c}_{ey,l,dp,db}^{II\_GEN\_TDeO}$	Share parameter of intermediate composites inputs gne (or TD&O or GEN) on TD&O sector production function
$\bar{c}_{ey}^{VA\_TDeO}$	Share parameter of value added composite input on TD&O sector production function

Generation sector parameters:

$\bar{c}_{pf,l,gp,gb,t}^{pf\_GEN\_tech}$	Share parameter of the production factors on GEN load block production function
$\bar{c}_{gne,l,gp,gb,t}^{II\_gne\_GEN\_tech}$, $\bar{c}_{l,p,b,t}^{II\_TDeO\_GEN\_tech}$, $\bar{c}_{l,dp,db,gp,gb,t}^{II\_GEN\_GEN\_tech}$	Share parameter of intermediate composites inputs gne (or TD&O or GEN) on GEN load block production function
$\bar{c}_{l,p,b,t}^{VA\_GEN\_tech}$	Share parameter of value added composite input on GEN load block production function

$\bar{c}^{ii\_tech\_GEN}_{l,p,b,t}$	Technology participation on load block
$\overline{mkt\_surplus}_{ey,l,gp,gb}$	Market surplus and non-accounted costs at each load block
$\bar{q}^{M_{GEN}}_{ey,l,gp,gb}$	Quantity of good electricity imported from the exterior
$\bar{p}^{M\_elect}_{ey,l,gp,gb}$	Price of imported electricity
$\bar{q}^{EX\_GEN}_{ey,l,gp,gb}$	Quantity of good electricity imported from the exterior
$\bar{p}^{EX\_GEN}_{ey,l,gp,gb}$	Price of imported electricity
	Government Behavior:
$\bar{\mathrm{q}}^{\mathrm{G}}_{\mathrm{ey,pf}}$	Quantity of production factor pf initially owned by the government
$\bar{\mathrm{q}}^{\mathrm{G}}_{\mathrm{ey,gne}}$, $\bar{\mathrm{q}}^{\mathrm{G\_TDeO}}_{ey}$, $\bar{\mathrm{q}}^{\mathrm{G\_GEN}}_{\mathrm{ey,l,p,b}}$	Government initial demand for good gne, TD&O or GEN
	Transfers:
$\overline{transf}^{G\_sne}_{ey,sne}$, $\overline{transf}^{G\_GEN}_{ey,l,gp,gb}$, $\overline{\mathrm{transf}}^{\mathrm{G\_TDeO}}_{ey}$	Net transfers from the government to productive sectors
$\overline{\mathrm{transf}}^{\mathrm{G-H}}_{ey}$	Net transfers from the government to the households
$\overline{\mathrm{transf}}^{\mathrm{Ext-G}}_{ey}$	Net transfers from the exterior to the government
$\overline{\mathrm{transf}}^{\mathrm{Ext-H}}_{ey}$	Net transfers from the exterior to the households
$\overline{\mathrm{transf}}^{\mathrm{Ext-K}}_{ey}$	Net capital transfers from the exterior
$\overline{emiss\_allow}_{ey,t,l,gp,gb}$	Emission Allowances
	Taxes:
$\bar{tx}^{SC\_SNE}_{ey,sne}$, $\bar{tx}^{SC\_TDeO}_{ey}$, $\bar{tx}^{SC\_GEN}_{ey,l,p,b,t}$	Social contribution tax rate
$\bar{\mathrm{tx}}^{\mathrm{Pdction}}_{\mathrm{ey,sne}}$, $\bar{tx}^{\mathrm{Pdction\_TDeO}}_{ey}$, $\bar{tx}^{Pdction\_GEN}_{ey,l,p,b,t}$	Production tax
$\bar{\mathrm{tx}}^{\mathrm{Pdct}}_{\mathrm{ey,sne}}$, $\bar{tx}^{\mathrm{Pdct\_TDeO}}_{ey}$, $\bar{tx}^{Pdct\_GEN}_{ey,l,p,b}$	Intermediate inputs product tax rate by sector
$\bar{\mathrm{tx}}^{\mathrm{Pdct}}_{\mathrm{ey,Exp}}$	Exports products tax rate
$\bar{\mathrm{tx}}^{\mathrm{H,G,I,EX}}_{ey}$	Household, Government, Investment and Exports final goods tax rate
	Saves-Investments:
$\bar{\theta}_{\mathrm{ey,gne}}$	Share parameter of demand for investment good gne

Prices:

$\bar{p}^{M}_{ey,gne}$, $\bar{p}^{M\_elect}_{ey,l,gp,gb}$	International price of the imported good
$\bar{p}^{EX}_{ey,gne}$, $\bar{p}^{EX\_elect}_{ey,l,gp,gb}$	International price of exported good
$\bar{p}^{CO2}_{ey}$	CO2 price

Variables:

Household:

$Q^{H}_{ey,gne}$	Household domestic non electricity goods demand
$Q^{H\_GEN}_{ey,l,p,b}$	Household domestic electricity goods demand at location l - season p and load block b
$Q^{H\_TDeO}_{ey}$	Household domestic electricity goods demand of transmission distribution and other electricity services
$P_{ey,pf}$	Price of production factor pf
Y^{H}_{ey}	Total household income

Non electricity productive sectors:

$Q^{pf\_SNE}_{ey,pf,sne}$	Quantity of production factor pf used in a specific sector sne
$Q^{VA}_{ey,sne}$	Quantity of value added composite good produced by sector sne
$P^{VA}_{ey,sne}$	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

$Q_{ey}^{VA\_TDeO}$	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 used 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 used by the transmission distribution and other electricity services
$Q_{ey}^{II\_TDeO\_TDeO}$	Quantity of transmission, distribution and other electricity services good intermediary input used by the electricity transmission, distribution and other electricity services
$Q_{ey}^{S\_TDeO}$	Quantity of the commodity produced by the transmission distribution and other electricity services
$P_{ey}^{S\_TDeO}$	Price of commodity produced by the transmission distribution and other electricity services (without foreign aggregations and production taxes)
$Q_{ey}^{D\_TDeO}$	Quantity of aggregated imported and domestic produced supply of transmission distribution and other electricity services
$P_{ey}^{D\_TDeO}$	Price of aggregated transmission distribution and other electricity services
$Q_{ey}^{Q\_TDeO}$	Quantity of final domestic market supply of transmission distribution and other electricity services
$P_{ey}^{Q\_TDeO}$	Price of final domestic transmission distribution and other electricity services

Electricity generation productive sector:

$Q_{ey,pf,l,p,b,t}^{pf\_GEN\_tech}$	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 used 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 used 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 used 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

$Q^{\text{Q\_GEN}}_{\text{ey,l,p,b}}$	Quantity of final domestic market supply of electricity good at location l - season p and load block b
$P^{\text{Q\_GEN}}_{\text{ey,l,p,b}}$	Price of final domestic electricity good at location l - season p and load block b

<u>Government:</u>

Y^{G}_{ey}	Total government income
E^{G}_{ey}	Total government expenditure
Y^{TAX}_{ey}	Total government taxes income

<u>Savings and Investments</u>

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
$\text{Q}^{\text{I}}_{\text{ey,gne}}$	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.

Simulation 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
$\overline{\text{dur}}_{\text{l,p,b}}$	Load block duration (hours)
$\overline{\text{min}\,\_sav}$	Minimum savings required to make the demand displacement

Simulation Variables:

$Q^{DR\text{\_INCREASED\_LOAD}}_{ey,l,p,b}$	Increased demand in load block due to demand response displacement (MW)
$Q^{DR\text{\_DECREASED\_LOAD}}_{ey,l,p,b}$	Decreased demand in load block due to demand response displacement (MW)
$Q^{DR\text{\_CONSERVED\_LOAD}}_{ey,l,p,b}$	Conserved demand in load block due to demand response displacement (MW)

AV.2 The GEMED model equations

Household behavior:

Household demand equations

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

$$Q^{H\_GEN}_{ey,l,p,b}=\frac{\bar{c}^{H\_GEN}_{ey,l,p,b}\left(1-\bar{s}^{H}_{ey}\right)Y^{H}_{ey}}{\left(1+\overline{tx}^{H}_{ey}\right)P^{Q\_GEN}_{ey,l,p,b}}\quad\perp\quad Q^{H\_GEN}_{ey,l,p,b}\quad,\forall ey,l,p,b \tag{AV-2}$$

$$Q^{H\_TDeO}_{ey}=\frac{\bar{c}^{H\_TDeO}_{ey}\left(1-\bar{s}^{H}_{ey}\right)Y^{H}_{ey}}{\left(1+\overline{tx}^{H}_{ey}\right)P^{H\_TDeO}_{ey}}\quad\perp\quad Q^{H\_TDeO}_{ey}\quad,\forall ey \tag{AV-3}$$

Household disposable Income

$$\begin{aligned}Y^{H}_{ey}&=\sum_{pf}P_{ey,pf}\bar{q}^{H}_{ey,pf}+\overline{transf}^{G-H}_{ey}\\&+\overline{psc}^{H}_{ey}\left(\sum_{sne}\overline{tx}^{SC\_SNE}_{ey,sne,pf=Labor}P_{ey,pf=Labor}Q^{pf\_SNE}_{ey,pf=Labor,sne}\right.\\&+\overline{tx}^{SC\_TDeO}_{ey,pf=Labor}P_{ey,pf=Labor}Q^{pf\_TDeO}_{ey,pf=Labor}\\&\left.+\sum_{l,p,b,t}\overline{tx}^{SC\_GEN}_{ey,l,p,b,t,pf=Labor}P_{ey,pf=Labor}Q^{pf\_GEN\_tech}_{ey,pf=Labor,l,p,b,t}\right)\\&+\overline{transf}^{Ext-H}_{ey}\quad\perp\quad Y^{H}_{ey}\quad,\forall ey\end{aligned} \tag{AV-4}$$

Household savings propensity

$$S^{H}_{ey}=\bar{s}^{H}_{ey}Y^{H}_{ey}\quad\perp\quad S^{H}_{ey}\quad,\forall ey \tag{AV-5}$$

Non-electricity production sector:

Non-electricity production sector value-added (production factors use: capital and labor)

$$\begin{aligned}&\left(Q^{pf\_SNE}_{ey,pf=Labor,sne}\right)^{\frac{1}{\bar{\sigma}^{VA}_{sne}}}\left(1-\bar{a}^{VA}_{sne,pf=Labor}\right)\left(\left(1+\overline{tx}^{SC\_SNE}_{ey,sne,pf=Labor}\right)P_{ey,pf=labor}\right)\\&=\left(Q^{pf\_SNE}_{ey,pf=Capital,sne}\right)^{\frac{1}{\bar{\sigma}^{VA}_{sne}}}\left(\bar{a}^{VA}_{sne,pf=Labor}\right)\left(P_{ey,pf=Capital}\right)\\&\perp\quad Q^{pf\_SNE}_{ey,pf=Labor,sne}\quad,\forall ey,sne\end{aligned} \tag{AV-6}$$

$$CES\left(Q_{ey,pf,sne}\right)-Q^{VA}_{ey,sne}=0\quad\perp\quad Q^{pf\_SNE}_{ey,pf=Capital,sne}\quad,\forall ey,sne \tag{AV-7}$$

$$\begin{aligned}P^{VA}_{ey,sne}Q^{VA}_{ey,sne}&=\left(1+\overline{tx}^{SC\_SNE}_{ey,sne}\right)P_{ey,pf=Labor}Q^{pf\_SNE}_{ey,pf=Labor,sne}\\&+P_{ey,pf=Capital}Q^{pf\_SNE}_{ey,pf=Capital,sne}\quad\perp\quad Q^{VA}_{ey,sne}\quad,\forall ey,sne\end{aligned} \tag{AV-8}$$

Non-electricity production sector intermediary inputs use

$$Q^{II}_{ey,gne,sne}=\bar{c}^{II}_{ey,gne,sne}Q^{S}_{ey,sne}\quad\perp\quad Q^{II}_{ey,gne,sne}\quad,\forall ey,gne,sne \tag{AV-9}$$

$$Q^{II\_GEN\_SNE}_{ey,l,dp,db,sne}=\bar{c}^{II\_GEN\_sne}_{ey,l,dp,db,sne}Q^{S}_{ey,sne}\quad\perp\quad Q^{II\_GEN\_SNE}_{ey,l,dp,db,sne}\quad,\forall\ ey,l,dp,db,sne \tag{AV-10}$$

$$Q^{II\_TDeO\_SNE}_{ey,sne}=\bar{c}^{II\_TDeO\_sne}_{ey,sne}Q^{S}_{ey,sne}\quad\perp\quad Q^{II\_TDeO\_SNE}_{ey,sne}\quad,\forall\ ey,sne \tag{AV-11}$$

Non-electricity production sector production quantity and price AV-12

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

$$\begin{aligned} P_{ey,sne}^{S} Q_{ey,sne}^{S} + \overline{transf}_{ey,sne}^{G\_sne} - P_{\mathrm{ey},sne}^{VA} Q_{ey,sne}^{VA} - \sum_{gne} \left(1 + \bar{tx}_{ey,sne}^{Pdct}\right) P_{ey,gne}^{Q} Q_{ey,gne,sne}^{II} \\ - \left(1 + \bar{tx}_{ey,sne}^{Pdct}\right) P_{ey}^{Q_{TDeO}} Q_{ey,sne}^{II_{TDeO}{}_{SNE}} - \sum_{l,p,b} \left(1 + \bar{tx}_{ey,sne}^{Pdct}\right) P_{ey,l,p,b}^{Q_{GEN}} Q_{ey,l,p,b,sne}^{II_{GEN}{}_{SNE}} \\ - \overline{emiss\ rate}_{ey,sne}^{CO2} \bar{p}_{ey}^{CO2} Q_{ey,sne}^{S} \leq 0 \ \perp \ Q_{ey,sne}^{S} \geq 0 \ ,\forall ey, sne \end{aligned} \tag{AV-13}$$

Non-electricity production sector imports Armington aggregation:

$$\left(Q_{ey,gne}^{S}\right)^{\frac{1}{\bar{\sigma}_{sne}^{D}}} \left(1 - \bar{a}_{gne}^{D}\right)\left(P_{ey,gne}^{S}\right) = \left(Q_{ey,gne}^{M}\right)^{\frac{1}{\bar{\sigma}_{sne}^{D}}} \left(\bar{a}_{gne}^{D}\right)\left(\bar{p}_{ey,gne}^{M}\right) \perp Q_{ey,gne}^{M} \quad ,\forall ey, gne \tag{AV-14}$$

$$Q_{ey,gne}^{D} - CES\left(Q_{ey,gne}^{S}, Q_{ey,gne}^{M}\right) = 0 \perp P_{ey,gne}^{S} \quad ,\forall ey, gne \tag{AV-15}$$

$$P_{ey,gne}^{D} Q_{ey,gne}^{D} - P_{ey,gne}^{S} Q_{ey,gne}^{S} - \bar{tx}_{ey,gne}^{Pdction} - \bar{p}_{ey,gne}^{M} Q_{ey,gne}^{M} = 0 \perp Q_{ey,gne}^{D} \quad ,\forall ey, gne \tag{AV-16}$$

Non-electricity production sector exports CET disaggregation:

$$\left(\bar{b}_{gne}^{Q}\right)^{\bar{\sigma}_{gne}^{Q}} \left(\left(1 + \bar{tx}_{ey,Exp}^{Pdct}\right)\bar{p}_{ey,gne}^{EX}\right)^{\bar{\sigma}_{gne}^{Q}} Q_{ey,gne}^{Q} = \left(1 - \bar{b}_{gne}^{Q}\right)^{\bar{\sigma}_{gne}^{Q}} \left(P_{ey,gne}^{Q}\right)^{\bar{\sigma}_{gne}^{Q}} Q_{ey,gne}^{EX} \perp Q_{ey,gne}^{EX} \ ,\forall ey, \mathrm{gne} \tag{AV-17}$$

$$Q_{ey,gne}^{D} - CET\left(Q_{ey,gne}^{Q}, Q_{ey,gne}^{EX}\right) = 0 \ \perp \ P_{ey,gne}^{D} \ ,\forall ey, gne \tag{AV-18}$$

Non-electricity production sector final price:

$$P_{ey,gne}^{Q} Q_{ey,gne}^{Q} + \bar{p}_{ey,gne}^{EX} Q_{ey,gne}^{EX} - P_{ey,gne}^{D} Q_{ey,gne}^{D} = 0 \quad \perp \quad Q_{ey,gne}^{Q} \ ,\forall ey, gne \tag{AV-19}$$

Transmission, distribution and other electricity services:

TD&O value-added (production factors use: capital and labor)

$$Q_{ey,pf}^{pf\_TDeO} = \bar{c}_{ey,pf}^{pf\_TDeO} Q_{ey}^{VA\_TDeO} \quad \perp \quad Q_{ey,pf}^{pf\_TDeO} \qquad ,\forall ey, pf \tag{AV-20}$$

$$\begin{aligned} & P_{ey}^{VA\_\mathrm{TDeO}} Q_{ey}^{VA\_TDeO} \\ & \quad = \left(1 + \bar{tx}_{ey}^{SC\_TDeO}\right) P_{ey,pf\_Labor} Q_{ey,pf=Labor}^{pf\_TDeO} \\ & \quad + P_{ey,pf=Capital} Q_{ey,pf=Capital}^{pf\_TDeO} \quad \perp \quad Q_{ey}^{VA\_TDeO} \qquad ,\forall ey \end{aligned} \tag{AV-21}$$

TD&O intermediary inputs use

$$Q_{ey,gne}^{II\_GNE\_TDeO} = \bar{c}_{ey,gne}^{II\_gne\_TDeO} Q_{ey}^{S\_TDeO} \quad \perp \quad Q_{ey,gne}^{II\_GNE\_TDeO} \qquad ,\forall ey, gne \tag{AV-22}$$

$$Q_{ey,l,dp,db}^{II\_GEN\_TDeO} = \bar{c}_{ey,l,dp,db}^{II\_GEN\_TDeO} Q_{ey}^{S\_TDeO} \quad \perp \quad Q_{ey,l,dp,db}^{II\_GEN\_TDeO} \quad ,\forall\ ey, l, dp, db \tag{AV-23}$$

$$Q_{ey}^{II\_TDeO\_\mathrm{TDeO}} = \bar{c}_{ey}^{II\_TDeO\_TDeO} Q_{ey}^{S\_TDeO} \quad \perp \quad Q_{ey}^{II\_TDeO\_TDeO} \qquad ,\forall ey \tag{AV-24}$$

TD&O production quantity and price

$$Q_{ey}^{VA\_TDeO} = \bar{c}_{ey}^{VA\_TDeO} Q_{ey}^{S\_TDeO} \quad \perp \quad P_{ey}^{VA\_TDeO} \qquad ,\forall ey \tag{AV-25}$$

$$\begin{aligned} & P_{ey}^{S\_TDeO} Q_{ey}^{S\_TDeO} + \overline{transf}_{ey}^{G-TDeO} - P_{ey}^{VA\_TDeO} Q_{ey}^{VA\_TDeO} \\ & \quad - \sum_{gne} \left(1 + \bar{tx}_{ey}^{Pdct\_\mathrm{TDeO}}\right) P_{ey,gne}^{Q} Q_{ey,gne}^{II\_GNE\_TDeO} \\ & \quad - \left(1 + \bar{tx}_{ey}^{Pdct\_TDeO}\right) P_{ey}^{Q\_TDeO} Q_{ey}^{II\_TDeO\_TDeO} \\ & \quad - \sum_{l,dp,db} \left(1 + \bar{tx}_{ey}^{Pdct\_TDeO}\right) P_{ey,l,dp,db}^{Q\_GEN} Q_{ey,l,gp,gb}^{II\_GEN\_TDeO} \\ & \quad - \overline{emiss\ rate}_{ey}^{CO2\_TDeO} \bar{p}_{ey}^{CO2} Q_{ey}^{S\_TDeO} \leq 0 \ \perp \ Q_{ey}^{S\_TDeO} \geq 0 \qquad ,\forall ey \end{aligned} \tag{AV-26}$$

$$Q_{ey}^{D\_TDeO} = Q_{ey}^{S\_TDeO} \ \perp \ P_{ey}^{S\_TDeO} \qquad ,\forall ey \tag{AV-27}$$

$$P_{ey}^{D\_TDeO} Q_{\mathrm{ey}}^{D\_TDeO} = \left(P_{ey}^{S\_TDeO} Q_{ey}^{S\_TDeO}\right) + \bar{tx}_{ey}^{Pdction\_TDeO} \ \perp \ Q_{ey}^{D\_TDeO} \quad ,\forall ey \tag{AV-28}$$

TD&O final quantity and price:

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

AV-29

$$P_{ey}^{Q\_TDeO} Q_{ey}^{Q\_TDeO} = P_{ey}^{D\_TDeO} Q_{ey}^{D\_TDeO} \quad \perp \quad Q_{ey}^{Q\_\mathrm{TDeO}} \quad ,\forall ey$$

AV-30

Generation Electricity sector:

GEN value-added (production factors use: capital and labor)

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

AV-31

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

AV-32

GEN intermediary inputs use

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

AV-33

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

AV-34

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

AV-35

GEN production quantity and price

$$Q_{ey,l,p,b,t}^{VA_{GEN_{tech}}} = \bar{c}_{l,p,b,t}^{VA_{GEN_{tech}}} Q_{ey,l,p,b,t}^{S_{GEN_{tech}}} \quad \perp \quad P_{ey,l,gp,gb,t}^{VA\_GEN\_tech} \quad ,\forall\ ey, l, p, b, t$$

AV-36

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

AV-37

$$Q_{ey,l,gp,gb,t}^{S\_GEN\_tech} = \bar{c}_{l,p,b,t}^{ii\_tech\_GEN} Q_{ey,l,gp,g\mathrm{b}}^{S\_GEN} \quad \perp \quad \mathrm{P}_{ey,l,p,b,t}^{S\_GEN\_tech} \quad ,\forall\ ey, l, gp, gb$$

AV-38

$$P_{ey,l,gp,gb}^{S\_GEN} Q_{ey,l,gp,gb}^{S\_GEN} = \left(\sum_{t} P_{ey,l,gp,gb,t}^{S\_GEN\_tech} Q_{ey,l,gp,g\mathrm{b},t}^{S\_GEN\_tech}\right) - \sum_{t} \overline{emiss\_allow}_{ey,t,l,gp,gb}$$
$$\perp \quad Q_{ey,l,p,b}^{S\_GEN} \ ,\forall\ ey, l, gp, gb$$

AV-39

GEN imports aggregation

$$Q_{ey,l,gp,gb}^{D\_GEN} = Q_{ey,l,gp,gb}^{S\_GEN} + \bar{q}_{ey,\mathrm{l},\mathrm{gp},gb}^{M\_GEN} \quad \perp \quad P_{ey,l,p,b}^{S\_GEN} \quad ,\forall ey, l, gp, gb$$

AV-40

$$P_{ey,l,gp,gb}^{D\_GEN} Q_{ey,l,gp,gb}^{D\_GEN} = P_{ey,l,gp,gb}^{S\_GEN} Q_{ey,l,gp,gb}^{S\_GEN} + \overline{t\mathrm{x}}_{l,gp,gb}^{Pdction\_GEN} + \bar{p}_{ey,l,gp,gb}^{M\_elect} \bar{q}_{ey,l,gp,gb}^{M\_elect}$$
$$\perp \quad Q_{ey,l,p,b}^{D\_GEN} \quad ,\forall ey, l, gp, gb$$

AV-41

GEN exports disaggregation

$$Q_{ey,l,gp,gb}^{Q\_GEN} = Q_{ey,l,\mathrm{gp},gb}^{D\_GEN} - \bar{q}_{ey,l,gp,gb}^{EX\_GEN} \quad \perp \quad P_{ey,l,p,b}^{D\_GEN} \quad ,\forall ey, l, gp, gb$$

AV-42

GEN final price

AV-43

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

Government:

Government income

$$Y_{ey}^{G} = \sum_{\mathrm{pf}} \mathrm{P}_{\mathrm{ey,pf}} \bar{\mathrm{q}}_{\mathrm{ey,pf}}^{\mathrm{G}} + \overline{\mathrm{transf}}_{ey}^{Ext-G} + \mathrm{Y}_{ey}^{TAX} \quad \perp \quad \mathrm{Y}_{ey}^{G} \quad ,\forall \mathrm{ey} \tag{AV-44}$$

Government expenditure

$$\begin{aligned} \mathrm{E}_{ey}^{G} = & \sum_{\mathrm{gne}} \left(1 + \overline{\mathrm{tx}}_{ey}^{G}\right) \mathrm{P}_{\mathrm{ey,gne}}^{\mathrm{Q}} \bar{\mathrm{q}}_{\mathrm{ey,gne}}^{\mathrm{G}} + \left(1 + \overline{\mathrm{tx}}_{ey}^{G}\right) \mathrm{P}_{ey}^{\mathrm{Q\_TDeO}} \bar{\mathrm{q}}_{ey}^{\mathrm{G\_TDeO}} \\ & + \sum_{\mathrm{l,p,b}} \left(1 + \overline{\mathrm{tx}}_{ey}^{G}\right) \mathrm{P}_{\mathrm{ey,l,p,b}}^{\mathrm{Q\_GEN}} \bar{\mathrm{q}}_{\mathrm{ey,l,p,b}}^{\mathrm{G\_GEN}} + \overline{\mathrm{transf}}_{ey}^{\mathrm{G-H}} \\ & + \overline{\mathrm{psc}}_{ey}^{H} \left(\sum_{\mathrm{sne}} \overline{\mathrm{tx}}_{\mathrm{ey,sne,pf=Labor}}^{\mathrm{SC\_SNE}} \mathrm{P}_{\mathrm{ey,pf=Labor}} \mathrm{Q}_{\mathrm{ey,pf=Labor,sne}}^{\mathrm{pf\_SNE}} \right. \\ & + \overline{\mathrm{tx}}_{\mathrm{ey,pf=Labor}}^{\mathrm{SC\_TDeO}} \mathrm{P}_{\mathrm{ey,pf=Labor}} \mathrm{Q}_{\mathrm{ey,pf=Labor}}^{\mathrm{pf\_TDeO}} \\ & \left. + \sum_{\mathrm{l,p,b,t}} \overline{\mathrm{tx}}_{\mathrm{ey,l,p,b,t,pf=Labor}}^{\mathrm{SC\_GEN}} \mathrm{P}_{\mathrm{ey,pf=Labor}} \mathrm{Q}_{\mathrm{ey,pf=Labor,l,p,b,t}}^{\mathrm{pf\_GEN\_tech}} \right) + \sum_{sne} \overline{transf}_{ey,sne}^{G\_sne} \\ & + \sum_{l,gp,gb} \overline{transf}_{ey,l,gp,gb}^{G\_GEN} + \sum_{t,l,gp,gb} \overline{emiss\_allow}_{ey,t,l,gp,gb} \\ & + \overline{\mathrm{transf}}_{ey}^{\mathrm{G\_TDeO}} \quad \perp \quad \mathrm{E}_{ey}^{G} \quad ,\forall \mathrm{ey} \end{aligned} \tag{AV-45}$$

Government savings

$$\mathrm{S}_{ey}^{G} = \mathrm{Y}_{ey}^{G} - \mathrm{E}_{ey}^{G} \quad \perp \quad \mathrm{S}_{ey}^{G} \quad ,\forall \mathrm{ey} \tag{AV-46}$$

Government tax income

$$\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}} \\ & + \overline{\mathrm{tx}}^{\mathrm{Pdction\_TDeO}} + \sum_{\mathrm{l,p,b}} \overline{\mathrm{tx}}_{\mathrm{l,gp,gb}}^{\mathrm{Pdction\_GEN}} \end{aligned} \tag{AV-47}$$

$$+\sum_{\mathrm{gne}} \overline{\mathrm{tx}}^{\mathrm{Pdct}}_{\mathrm{Exp}} \overline{\mathrm{p}}^{\mathrm{EX}}_{\mathrm{ey,gne}} \mathrm{Q}^{\mathrm{EX}}_{\mathrm{ey,gne}} + \sum_{\mathrm{l,p,b}} \overline{\mathrm{tx}}^{\mathrm{Pdct}}_{\mathrm{Exp}} \overline{\mathrm{p}}^{\mathrm{EX\_GEN}}_{\mathrm{ey,l,gp,gb}} \overline{\mathrm{q}}^{\mathrm{EX\_GEN}}_{\mathrm{ey,l,gp,gb}} + \sum_{\mathrm{gne}} \overline{\mathrm{tx}}^{\mathrm{H}} \mathrm{P}^{\mathrm{Q}}_{\mathrm{ey,gne}} \mathrm{Q}^{\mathrm{H}}_{\mathrm{ey,gne}}$$

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

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

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

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

Savings and Investments:

Total savings

$$\mathrm{S}_{ey} = \mathrm{S}^{H}_{ey} + \mathrm{S}^{G}_{ey} + \mathrm{S}^{Ext}_{ey} + \overline{\mathrm{transf}}^{\mathrm{Ext\_K}}_{ey} \quad \perp \quad \mathrm{S}_{ey} \quad ,\forall \mathrm{ey} \tag{AV-48}$$

External savings

$$\mathrm{S}^{Ext}_{ey} = \sum_{\mathrm{gne}} \overline{\mathrm{p}}^{\mathrm{M}}_{\mathrm{ey,gne}} \mathrm{Q}^{\mathrm{M}}_{\mathrm{ey,gne}} + \sum_{\mathrm{l,gp,gb}} \overline{\mathrm{p}}^{\mathrm{M\_elect}}_{\mathrm{ey,l,gp,gb}} \overline{\mathrm{q}}^{\mathrm{M\_elect}}_{\mathrm{ey,l,gp,gb}} - \sum_{\mathrm{gne}} \left(1 + \overline{\mathrm{tx}}^{\mathrm{Pdct}}_{\mathrm{ey,Exp}}\right) \overline{\mathrm{p}}^{\mathrm{EX}}_{\mathrm{ey,gne}} \mathrm{Q}^{\mathrm{EX}}_{\mathrm{ey,gne}}$$
$$- \sum_{\mathrm{l,gp,gb}} \left(1 + \overline{\mathrm{tx}}^{\mathrm{Pdct}}_{\mathrm{ey,Exp}}\right) \overline{\mathrm{p}}^{\mathrm{EX\_elect}}_{\mathrm{ey,l,gp,gb}} \overline{\mathrm{q}}^{\mathrm{EX\_elect}}_{\mathrm{ey,l,gp,gb}} - \overline{\mathrm{transf}}^{\mathrm{Ext-G}}_{ey} - \overline{\mathrm{transf}}^{\mathrm{Ext-H}}_{ey}$$
$$- \overline{\mathrm{transf}}^{\mathrm{Ext-K}}_{ey} \quad \perp \quad \mathrm{S}^{Ext}_{ey} \quad ,\forall \mathrm{ey} \tag{AV-49}$$

Investments

$$\mathrm{Q}^{\mathrm{I}}_{\mathrm{ey,gne}} = \frac{\overline{\theta}_{\mathrm{ey,gne}}}{(1+\overline{\mathrm{tx}}^{Inv}_{ey})\mathrm{P}^{\mathrm{Q}}_{\mathrm{ey,gne}}} \mathrm{I}_{ey} \quad \perp \quad \mathrm{Q}^{\mathrm{I}}_{\mathrm{ey,gne}} \quad ,\forall \mathrm{ey,gne} \tag{AV-50}$$

Market clearing conditions:

Production factors market clearing

$$\sum_{\mathrm{sne}} \mathrm{Q}_{\mathrm{ey,pf,sne}} + \mathrm{Q}^{\mathrm{pf\_TDeO}}_{\mathrm{ey,pf}} + \sum_{\mathrm{l,gp,gb,t}} \mathrm{Q}^{\mathrm{pf\_tech}}_{\mathrm{ey,pf,l,gp,gb,t}} + \left(\sum_{\mathrm{l,gp,gb}} \frac{\overline{mkt\_surplus}_{ey,l,gp,gb}}{P_{ey,pf}} \right)_{if\ pf=Capital} \leq \bar{\mathrm{q}}^{\mathrm{H}}_{\mathrm{ey,pf}} + \bar{\mathrm{q}}^{\mathrm{G}}_{\mathrm{ey,pf}} \quad \perp \ \mathrm{P}_{\mathrm{ey,pf}} \quad , \forall \mathrm{ey, pf} \qquad \text{AV-51}$$

Non-electricity final goods market clearing

$$\mathrm{Q}^{\mathrm{H}}_{\mathrm{ey,gne}} + \bar{\mathrm{q}}^{\mathrm{G}}_{\mathrm{ey,gne}} + \sum_{\mathrm{sne}} \mathrm{Q}^{\mathrm{II}}_{\mathrm{ey,gne,sne}} + \mathrm{Q}^{\mathrm{II\_GNE\_TDeO}}_{\mathrm{ey,gne}} + \sum_{\mathrm{l,p,b,t}} \mathrm{Q}^{\mathrm{II\_GNE\_GEN\_tech}}_{\mathrm{ey,gne,l,p,b,t}} + \mathrm{Q}^{\mathrm{I}}_{\mathrm{ey,gne}} \leq \mathrm{Q}^{\mathrm{Q}}_{\mathrm{ey,gne}} \quad \perp \quad \mathrm{P}^{\mathrm{Q}}_{\mathrm{ey,gne}} \quad , \forall \mathrm{ey, gne} \qquad \text{AV-52}$$

GEN final goods market clearing

$$\mathrm{Q}^{\mathrm{H\_GEN}}_{\mathrm{ey,l,p,b}} + \bar{\mathrm{q}}^{\mathrm{G\_elec}}_{\mathrm{ey,l,p,b}} + \sum_{\mathrm{sne}} \mathrm{Q}^{\mathrm{II\_GEN\_SNE}}_{\mathrm{ey,l,p,b,sne}} + \mathrm{Q}^{\mathrm{II\_GEN\_TDeO}}_{\mathrm{ey,l,p,b}} + \sum_{\mathrm{gp,gb,t}} \mathrm{Q}^{\mathrm{II\_GEN\_GEN\_tech}}_{\mathrm{ey,l,p,b,gp,gb,t}} \leq \mathrm{Q}^{\mathrm{Q_{GEN}}}_{\mathrm{ey,l,p,b}} \quad \perp \quad \mathrm{P}^{\mathrm{Q\_GEN}}_{\mathrm{ey,l,p,b}} \quad , \forall \mathrm{ey, l, p, b} \qquad \text{AV-53}$$

TD&O final goods market clearing

$$\mathrm{Q}^{\mathrm{H\_TDeO}}_{ey} + \bar{\mathrm{q}}^{\mathrm{G\_TDeO}}_{ey} + \sum_{\mathrm{sne}} \mathrm{Q}^{\mathrm{II\_TDeO\_SNE}}_{\mathrm{ey,sne}} + \mathrm{Q}^{\mathrm{II\_TDeO\_TDeO}}_{ey} + \sum_{\mathrm{l,p,b,t}} \mathrm{Q}^{\mathrm{II\_TDeO\_GEN\_tech}}_{\mathrm{ey,l,p,b,t}} \leq \mathrm{Q}^{\mathrm{Q\_TDeO}}_{ey} \quad \perp \quad \mathrm{P}^{\mathrm{Q\_TDeO}}_{ey} \quad , \forall \mathrm{ey} \qquad \text{AV-54}$$

Investments-savings identity

$$\mathrm{I}_{ey} = \mathrm{S}_{ey} \quad \perp \quad \mathrm{I}_{ey} \quad , \forall \mathrm{ey} \qquad \text{AV-55}$$

Consumer Price Index (model numeraire):

$$\mathrm{CPI} = \sum_{gne} \bar{\mu}^{Q}_{gne} \mathrm{P}^{\mathrm{Q}}_{\mathrm{ey,gne}} + \sum_{l,p,b} \bar{\mu}^{Q\_GEN}_{gne} \mathrm{P}^{Q\_GEN}_{\mathrm{ey,l,p,b}} + \bar{\mu}^{Q\_TDeO} \mathrm{P}^{\mathrm{Q\_TDeO}}_{ey} \quad \perp \quad \mathrm{CPI} \qquad \text{AV-56}$$

Annex VI The H-GEMED Model

The H-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) and a complex behavior to the electricity generation decision.

The model equations follow the GEMED formulation (Annex V), except for the electricity generation sector that includes the mixed complementarity formulation of the electricity operation and investment model (equations AVI-45 to AVI-60 obtained from Annex IV) together with some additional linking equations (equations AVI-31 to AVI-44).

The dimensions, variables and equations of the model are presented below.

AVI.1 Sets, parameters and variables

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 (year, season or month)
b (db,gb)	Load block (group of hours inside each period)
pollut	Pollutants (CO2e_ETS, CO2e_non_ETS, PM10, SOx, NOx, CO, VOC, NH3)

Variables:

	<u>Household:</u>
$Q^{H}_{ey,gne}$	Household domestic non electricity goods demand
$Q^{H\_GEN}_{ey,l,p,b}$	Household domestic electricity goods demand at location l - season p and load block b
Q^{TDeO}_{ey}	Household domestic electricity goods demand of transmission distribution and other electricity services
$P_{ey,pf}$	Price of production factor pf
Y^{H}_{ey}	Total household income
	<u>Non electricity productive sectors:</u>
$Q^{pf\_SNE}_{ey,pf,sne}$	Quantity of production factor pf used in a specific sector sne
$Q^{VA}_{ey,sne}$	Quantity of value added composite good produced by sector sne
$P^{VA}_{ey,sne}$	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)
	<u>Imports Armington Aggregation:</u>
$Q^{M}_{ey,gne}$	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
	<u>Exports CET disaggregation:</u>
$Q^{EX}_{ey,gne}$	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
	<u>Transmission, distribution and other electricity services:</u>
$Q^{pf\_TDeO}_{ey,pf}$	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

$Q_{ey}^{II\_TDeO\_TDeO}$	Quantity of transmission, distribution and other electricity services good intermediary input used by the electricity transmission, distribution and other electricity services
$Q_{ey}^{S\_TDeO}$	Quantity of the commodity produced by the transmission distribution and other electricity services
$P_{ey}^{S\_TDeO}$	Price of commodity produced by the transmission distribution and other electricity services (without foreign aggregations and production taxes)
$Q_{ey}^{D\_TDeO}$	Quantity of aggregated imported and domestic produced supply of transmission distribution and other electricity services
$P_{ey}^{D\_TDeO}$	Price of aggregated transmission distribution and other electricity services
$Q_{ey}^{Q\_TDeO}$	Quantity of final domestic market supply of transmission distribution and other electricity services
$P_{ey}^{Q\_TDeO}$	Price of final domestic transmission distribution and other electricity services

Electricity generation productive sector:

$Q_{ey,pf,l,p,b,t}^{pf\_GEN\_tech}$	Quantity of production factor pf used in the electricity sector at location l - season p and load block b by the production technology t
$Q_{ey,gne,l,p,b,t}^{II\_GNE\_GEN\_tech}$	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
$Q_{ey,l,dp,db,gp,gb,t}^{II\_GEN\_GEN\_tech}$	Quantity of electricity good intermediary input at location l - season dp and load block db used 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 used 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
$Q_{ey,l,p,b}^{S\_GEN}$	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)
$Q_{ey,l,p,b}^{Q\_GEN}$	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
$PGEN_{y,t,f,l,p,b}$	Electricity power generation by each technology (MW)
$PPUMPED_{y,l,p,b}$	Pumping consumed electricity power (MW)
$RES_{y,l,p}$	Hydro technology reservoir level (MW)
$TCAP_{y,l,t}$	Total installed capacity potency
$PINS_{y,l,t}$	New installed capacity by year
$P_{ey,t,f}^{FUEL}$	Fuel Price
$Mkt\_Surplus_{y,l,p,b}$	Market Surplus
λ and μ	Bottom-up dual variables

	Imports:
$\mathrm{Q}^{\mathrm{M\_GEN}}_{\mathrm{ey,l,p,b}}$	Quantity of good electricity imported from the exterior
$\mathrm{P}^{\mathrm{M\_GEN}}_{\mathrm{ey,l,p,b}}$	Price of imported electricity
	Exports:
$\mathrm{Q}^{\mathrm{EX\_GEN}}_{\mathrm{ey,l,p,b}}$	Quantity of good electricity imported from the exterior
$\mathrm{P}^{\mathrm{EX\_GEN}}_{\mathrm{ey,l,p,b}}$	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)
	Consumer Price Index:
CPI	Consumer price index. Model numeraire.
	Simulation Variables:
$\mathrm{Y}^{Env\_tax}_{ey,pollut}$	Total environmental taxes revenues by pollutant
$\mathrm{sc\_subsidy}_{ey}$	Green tax reform social contributions subsidy rate
$\mathrm{s\_lump\_sum}_{ey}$	Green tax reform sector lump sum subsidies

AVI.2 The H-GEMED model equations

Household behavior:

Household demand equations

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

$$Q_{ey,l,p,b}^{H\_GEN} = \frac{\bar{c}_{ey,l,p,b}^{H\_GEN}\left(1-\bar{s}_{ey}^{H}\right)Y_{ey}^{H}}{\left(1+\bar{tx}_{ey}^{H}\right)P_{ey,l,p,b}^{Q\_GEN}} \quad ,\forall ey,l,p,b \tag{AVI-2}$$

$$Q_{ey}^{H\_\mathrm{TDeO}} = \frac{\bar{c}_{ey}^{H\_TDeO}\left(1-\bar{s}_{ey}^{H}\right)Y_{ey}^{H}}{\left(1+\bar{t\mathrm{x}}_{ey}^{H}\right)P_{ey}^{H\_TDeO}} \quad ,\forall ey \tag{AVI-3}$$

Household disposable Income

$$\begin{aligned}
Y_{ey}^{H} = {} & \sum_{pf} P_{ey,pf}\bar{q}_{ey,pf}^{H} + \overline{transf}_{ey}^{G-H} \\
& + \overline{psc}_{ey}^{H}\left(\sum_{sne}\left(\bar{tx}_{ey,sne,pf=Labor}^{SC_{SNE}} - sc_{subsidy_{ey}}\right.\right. \\
& - \left.\bar{tx}_{ey,sne,pf=Labor}^{SC_{SNE}} sc_{subsidy_{ey}}\right) P_{ey,pf=Labor} Q_{ey,pf=Labor,\mathrm{sne}}^{pf_{SNE}} \\
& + \left(\bar{tx}_{ey,sne,pf=Labor}^{SC_{TDeO}} - sc_{subsidy_{ey}}\right. \\
& - \left.\bar{tx}_{ey,sne,pf=Labor}^{SC_{TDeO}} sc_{subsidy_{ey}}\right) P_{ey,pf=Labor} Q_{ey,pf=Labor}^{pf_{TDeO}} \\
& + \sum_{l,\mathrm{p},b,t}\left(\bar{tx}_{ey,sne,pf=Labor}^{SC_{GEN}} - sc_{subsidy_{ey}}\right. \\
& - \left.\left.\bar{tx}_{ey,sne,pf=Labor}^{SC_{GEN}} sc_{subsidy_{ey}}\right) P_{ey,pf=Labor} Q_{ey,pf=Labor,l,p,b,t}^{pf_{GEN_{tech}}}\right) \\
& + \overline{transf}_{ey}^{Ext-H} - \sum_{pollut}\sum_{gne}\left(\overline{emiss\ rate}_{ey,gne,pollut}^{pollut_{H_{gne}}}\bar{p}_{ey,pollut}^{pollut} Q_{ey,gne}^{H}\right) \\
& - \sum_{pollut}\left(\overline{emiss\ rate}_{ey,pollut}^{pollut_{H_{TDeO}}}\bar{p}_{ey,pollut}^{pollut} Q_{ey}^{H_{TDeO}}\right) \\
& - \sum_{pollut}\sum_{l,p,b}\left(\overline{emiss\ rate}_{ey,l,p,b,pollut}^{pollut\_H\_GEN}\bar{p}_{ey,pollut}^{pollut} Q_{ey,l,p,b}^{H\_GEN}\right) \quad ,\forall ey
\end{aligned} \tag{AVI-4}$$

Household savings propensity

$$S_{ey}^{H} = \bar{s}_{ey}^{H} Y_{ey}^{H} \quad ,\forall ey \tag{AVI-5}$$

Non-electricity production sector:

Non-electricity production sector value-added (production factors use: capital and labor)

$$\begin{aligned}
& \left(Q_{ey,pf=Labor,sne}^{pf\_SNE}\right)^{\frac{1}{\bar{\sigma}_{sne}^{VA}}}\Big(1 \\
& - \bar{a}_{sne}^{VA_L}\Big)\left(\left(1+\bar{tx}_{ey,sne,pf=Labor}^{SC\_SNE}\right)\left(1-sc\_subsidy_{ey}\right)P_{ey,pf=labor}\right) \\
& = \left(Q_{ey,pf=Capital,sne}^{pf\_SNE}\right)^{\frac{1}{\bar{\sigma}_{sne}^{VA}}}\left(\bar{a}_{sne}^{VA\_L}\right)\left(P_{ey,pf=Capital}\right) \quad ,\forall ey, sne
\end{aligned} \tag{AVI-6}$$

$$CES\left(Q_{ey,pf,sne}\right) - Q_{ey,sne}^{VA} = 0 \quad \perp \quad p_{ey,sne}^{VA} \quad ,\forall ey, sne \tag{AVI-7}$$

$$\begin{aligned}
P_{ey,sne}^{VA} Q_{ey,sne}^{VA} = {} & \left(1+\bar{tx}_{ey,sne}^{SC\_SNE}\right)\left(1-sc\_subsidy_{ey}\right)P_{ey,pf=Labor} Q_{ey,pf=Labor,sne}^{pf\_SNE} \\
& + P_{ey,pf=Capital} Q_{ey,pf=Capital,sne}^{pf\_SNE} \quad ,\forall ey, sne
\end{aligned} \tag{AVI-8}$$

Non-electricity production sector intermediary inputs use

$$Q_{ey,gne,sne}^{II} = \bar{c}_{ey,gne,sne}^{II} Q_{ey,sne}^{S} \quad ,\forall ey, gne, sne \tag{AVI-9}$$

$$Q_{ey,l,dp,db,sne}^{II\_GEN\_SNE} = \bar{c}_{ey,l,dp,db,sne}^{II\_GEN\_sne} Q_{ey,sne}^{S} \quad ,\forall\ ey, l, dp, db, sne \tag{AVI-10}$$

$$Q_{ey,sne}^{II\_TDeO\_SNE} = \bar{c}_{ey,sne}^{II\_TDeO\_sne} Q_{ey,sne}^{S} \quad ,\forall\ ey, sne \tag{AVI-11}$$

Non-electricity production sector production quantity and price

$$Q^{VA}_{ey,sne} = \bar{c}^{VA}_{ey,sne} Q^{S}_{ey,sne} \qquad ,\forall ey, sne \tag{AVI-12}$$

$$\begin{aligned}
P^{S}_{ey,sne} Q^{S}_{ey,sne} + \overline{transf}^{G\_sne}_{ey,sne} - P^{VA}_{ey,sne} Q^{VA}_{ey,sne} - \sum_{gne} \left(1 + \bar{tx}^{Pdct}_{ey,sne}\right) P^{Q}_{ey,gne} Q^{II}_{ey,gne,sne} \\
- \left(1 + \bar{tx}^{Pdct}_{ey,sne}\right) P^{Q_{TDeO}}_{ey} Q^{II_{TDeO_{SNE}}}_{ey,sne} \\
- \sum_{l,p,b} \left(1 + \bar{tx}^{Pdct}_{ey,sne}\right) P^{Q_{GEN}}_{ey,l,p,b} Q^{II_{GEN_{SNE}}}_{ey,l,p,b,sne} \\
- \sum_{pollut} \left(\overline{emiss\ rate}^{pollut\_sne}_{ey,sne,pollut} \bar{p}^{pollut}_{ey,pollut} Q^{S}_{ey,sne}\right) \leq 0 \ \perp \ Q^{S}_{ey,sne} \\
\geq 0 \ ,\forall ey, sne
\end{aligned} \tag{AVI-13}$$

Non-electricity production sector imports Armington aggregation:

$$\begin{aligned}
\left(Q^{S}_{ey,gne}\right)^{\frac{1}{\bar{\sigma}^{VA}_{sne}}} \left(1 - \bar{a}^{D}_{gne}\right) \left(\left(1 + \bar{tx}^{Pdction}_{ey,sne}\right) P^{S}_{ey,gne}\right) \\
= \left(Q^{M}_{ey,gne}\right)^{\frac{1}{\bar{\sigma}^{VA}_{sne}}} \left(\bar{a}^{D}_{gne}\right) \left(\bar{p}^{M}_{ey,gne}\right) \quad ,\forall ey, gne
\end{aligned} \tag{AVI-14}$$

$$Q^{D}_{ey,gne} - CES\left(Q^{S}_{ey,gne}, Q^{M}_{ey,gne}\right) = 0 \perp \lambda^{D}_{ey,gne} \qquad ,\forall ey, gne \tag{AVI-15}$$

$$P^{D}_{ey,gne} Q^{D}_{ey,gne} - P^{S}_{ey,gne} Q^{S}_{ey,gne} - \bar{tx}^{Pdction}_{sne} - \bar{p}^{M}_{ey,gne} Q^{M}_{ey,gne} = 0 \qquad ,\forall ey, gne \tag{AVI-16}$$

Non-electricity production sector exports CET disaggregation:

$$\begin{aligned}
\left(\bar{b}^{Q}_{gne}\right)^{\bar{\sigma}^{Q}_{gne}} \left(\left(1 + \bar{tx}^{Pdct}_{ey,Exp}\right) \bar{p}^{EX}_{ey,gne}\right)^{\bar{\sigma}^{Q}_{gne}} Q^{Q}_{ey,gne} = (1 - \\
\bar{b}^{Q}_{gne})^{\bar{\sigma}^{Q}_{gne}} \left(P^{Q}_{ey,gne}\right)^{\bar{\sigma}^{Q}_{gne}} Q^{EX}_{ey,gne} \quad ,\forall ey, g\mathrm{ne}
\end{aligned} \tag{AVI-17}$$

$$Q^{D}_{ey,gne} - CET\left(Q^{Q}_{ey,gne}, Q^{EX}_{ey,gne}\right) = 0 \ \perp \ \lambda^{Q}_{ey,gne} \ ,\forall ey, gne \tag{AVI-18}$$

Non-electricity production sector final price:

$$\left(1 + s\_lump\_sum_{ey}\right) P^{Q}_{ey,gne} Q^{Q}_{ey,gne} + \bar{p}^{EX}_{ey,gne} Q^{EX}_{ey,gne} - P^{D}_{ey,gne} Q^{D}_{ey,gne} = 0 \qquad ,\forall ey, gne \tag{AVI-19}$$

Transmission, distribution and other electricity services:

TD&O value-added (production factors use: capital and labor)

$$Q^{pf\_TDeO}_{ey,pf} = \bar{c}^{pf\_TDeO}_{ey,pf} Q^{VA\_TDeO}_{ey} \qquad ,\forall ey, pf \tag{AVI-20}$$

$$\begin{aligned}
P^{VA\_TDeO}_{ey} Q^{VA\_TDeO}_{ey} \\
= \left(1 + \bar{tx}^{SC\_TDeO}_{ey}\right)\left(1 - sc\_subsidy_{ey}\right) P_{ey,pf\_Labor} Q^{pf\_TDeO}_{ey,pf=Labor} \\
+ P_{ey,pf=Capital} Q^{pf\_TDeO}_{ey,pf=Capital} \qquad ,\forall ey
\end{aligned} \tag{AVI-21}$$

TD&O intermediary inputs use

$$Q^{II\_GNE\_TDeO}_{ey,gne} = \bar{c}^{II\_gne\_TDeO}_{ey,gne} Q^{S\_TDeO}_{ey} \qquad ,\forall ey, gne \tag{AVI-22}$$

$$Q^{II\_GEN\_TDeO}_{ey,l,dp,db} = \bar{c}^{II\_GEN\_TDeO}_{ey,l,dp,db} Q^{S\_TDeO}_{ey} \qquad ,\forall\ ey, l, dp, db \tag{AVI-23}$$

$$Q^{II\_TDeO\_TDeO}_{ey} = \bar{c}^{II\_TDeO\_TDeO}_{ey} Q^{S\_TDeO}_{ey} \qquad ,\forall ey \tag{AVI-24}$$

TD&O production quantity and price

$$Q^{VA\_TDeO}_{ey} = \bar{c}^{VA\_TDeO}_{ey} Q^{S\_TDeO}_{ey} \qquad ,\forall ey \tag{AVI-25}$$

$$
\begin{aligned}
P_{ey}^{S\_TDeO} Q_{ey}^{S\_TDeO} &+ \overline{transf}_{ey}^{G-TDeO} - P_{ey}^{VA\_TDeO} Q_{ey}^{VA\_TDeO} \\
&- \sum_{gne} \left(1 + \bar{tx}_{ey}^{Pdct\_TDeO}\right) P_{ey,gne}^{Q} Q_{ey,gne}^{II\_GNE\_TDeO} \\
&- \left(1 + \bar{tx}_{ey}^{Pdct\_TDeO}\right) P_{ey}^{Q\_TDeO} Q_{ey}^{II\_TDeO\_TDeO} \\
&- \sum_{l,dp,db} \left(1 + \bar{tx}_{ey}^{Pdct\_TDeO}\right) P_{ey,l,dp,db}^{Q\_GEN} Q_{ey,l,gp,gb}^{II\_GEN\_TDeO} \\
&- \sum_{pollut} \left(\overline{emiss\ rate}_{ey,sne,pollut}^{pollut\_TDeO} \bar{p}_{ey,pollut}^{pollut} Q_{ey}^{S\_TDeO}\right) \leq 0 \ \perp \ Q_{ey}^{S\_TDeO} \\
&\geq 0 \quad ,\forall ey
\end{aligned}
\qquad \text{AVI-26}
$$

$$
Q_{ey}^{D\_TDeO} = Q_{ey}^{S\_TDeO} \quad ,\forall ey \qquad \text{AVI-27}
$$

$$
P_{ey}^{D\_TDeO} Q_{ey}^{D\_TDeO} = \left(P_{ey}^{S\_TDeO} Q_{ey}^{S\_TDeO}\right) + \bar{tx}^{Pdction\_TDeO} \quad ,\forall ey \qquad \text{AVI-28}
$$

TD&O final quantity and price:

$$
Q_{ey}^{Q\_TDeO} = Q_{ey}^{D\_TDeO} \quad ,\forall ey \qquad \text{AVI-29}
$$

$$
\left(1 + s\_lump\_sum_{ey}\right) P_{ey}^{Q\_TDeO} Q_{ey}^{Q\_TDeO} = P_{ey}^{D\_TDeO} Q_{ey}^{D\_TDeO} \quad ,\forall ey \qquad \text{AVI-30}
$$

Electricity generation sector:

Variables correspondence between bottom-up and top-down:

GEN production factors

$$
\begin{aligned}
Q_{ey,pf,l,p,b,t}^{pf\_GEN\_tech} &= \overline{\text{dist}_{\text{factor}}}_{ey,l,gp,gb} \overline{\text{dur}}_{l,gp,gb} \\
&\left[\left(\frac{\overline{\text{oem\_fom}}_{ey,l,t}^{\text{labor}} \frac{\text{TCAP}_{ey,l,t}}{10^3}}{\left(\bar{tx}_{ey,sne,pf=Labor}^{SC\_GEN} - \text{sc\_subsidy}_{ey} - \bar{tx}_{ey,sne,pf=Labor}^{SC\_GEN} \text{sc\_subsidy}_{ey}\right)} \right)_{pf=Labor} \right. \\
&+ \left(\overline{\text{overn\_costs}}_{ey,t} \overline{\text{idc}}_{t} \overline{\text{crf}}_{t} \left(\frac{\overline{\text{cap}}_{ey,l,t}^{\text{to\_be\_amort}}}{10^3} \right. \right. \\
&\left. \left. \left. + \sum_{\substack{y' \leq ey \\ y` \geq ey-l\_t}} \frac{\text{PINS}_{y',l,t}}{10^3} \right) \right)_{pf=Capital} \right] / P_{ey,pf}
\end{aligned}
\qquad \text{AVI-31}
$$

GEN Intermediary inputs AVI-32

$$
\begin{aligned}
&\mathrm{Q}^{\mathrm{II\_GNE\_GEN\_tech}}_{\mathrm{ey,gne,l,p,b,t}} \\
&= \left(\bar{\eta}_{\mathrm{ey,l,t}}\ \bar{\mathrm{p}}^{\mathrm{fuel}}_{\mathrm{ey,p,t,f}}\ \overline{\mathrm{dur}}_{\mathrm{l,gp,gb}} \sum_{\mathrm{f}} \frac{\mathrm{PGEN}_{\mathrm{ey,t,f,l,p,b}}}{10^6}\right)_{if\ gne=\text{coal,oil}-\text{nuclear and gas sectors}} \\
&+ \left(\overline{\mathrm{oem\_vom}}_{\mathrm{ey,t}} \overline{\mathrm{dur}}_{\mathrm{l,gp,gb}} \sum_{\mathrm{f}} \frac{\mathrm{PGEN}_{\mathrm{ey,t,f,l,p,b}}}{10^6}\right)_{if\ gne=\text{manufactures sector}} \\
&+ \left(\overline{\mathrm{dist\_factor}}_{\mathrm{ey,l,p,b}} \overline{\mathrm{oem\_fom}}^{\mathrm{equip}}_{\mathrm{ey,l,t}} \frac{\mathrm{TCAP}_{\mathrm{ey,l,t}}}{10^3}\right)_{if\ gne=\text{manufactures sector}} / P^{Q}_{ey,gne}
\end{aligned}
$$

$$
\begin{aligned}
&\mathrm{Q}^{\mathrm{II\_GEN\_GEN\_tech}}_{\mathrm{ey,l,dp,db,gp,gb,t}} \\
&= \frac{\overline{\mathrm{own\_cons}}\ \mathrm{P}^{\mathrm{S\_GEN}}_{\mathrm{ey,l,p,b}} \overline{\mathrm{dur}}_{\mathrm{l,gp,gb}} \sum_{\mathrm{f}} \frac{\mathrm{PGEN}_{\mathrm{ey,t,f,l,p,b}}}{10^6} + \mathrm{P}^{\mathrm{S\_GEN}}_{\mathrm{ey,l,p,b}} \overline{\mathrm{dur}}_{\mathrm{l,gp,gb}} \frac{\mathrm{PPUMPED}_{\mathrm{ey,l,p,b}}}{10^6}}{\mathrm{P}^{\mathrm{Q\_GEN}}_{\mathrm{ey,l,p,b}}}
\end{aligned} \qquad \text{AVI-33}
$$

$$
\mathrm{Q}^{\mathrm{II\_TDeO\_GEN\_tech}}_{\mathrm{ey,l,p,b,t}} = 0 \quad , \forall\ \mathrm{ey,l,p,b,t} \qquad \text{AVI-34}
$$

GEN production prices and quantities

$$
\mathrm{Q}^{\mathrm{S\_GEN\_tech}}_{\mathrm{ey,l,p,b,t}} = \sum_{\mathrm{f}} \frac{\mathrm{PGEN}_{\mathrm{ey,t,f,l,p,b}}}{10^6} \overline{\mathrm{dur}}_{\mathrm{l,p,b}} \qquad \text{AVI-35}
$$

$$
\mathrm{Q}^{\mathrm{S\_GEN}}_{\mathrm{ey,l,p,b}} = \sum_{t} \mathrm{Q}^{\mathrm{S\_GEN\_tech}}_{\mathrm{ey,l,p,b,t}} \qquad \text{AVI-36}
$$

$$
\mathrm{P}^{\mathrm{S\_GEN}}_{\mathrm{ey,l,p,b}} = \frac{\lambda^{Dem}_{ey,l,p,b} 10^6}{\overline{\mathrm{dur}}_{\mathrm{l,p,b}}} \qquad \text{AVI-37}
$$

GEN imports

$$
\mathrm{Q}^{\mathrm{M\_GEN}}_{\mathrm{ey,l,p,b}} = \overline{\mathrm{dur}}_{\mathrm{l,gp,gb}} \frac{\overline{\mathrm{pimp}}_{\mathrm{ey,l,p,b}}}{10^6} \qquad \text{AVI-38}
$$

$$
\mathrm{P}^{\mathrm{M\_GEN}}_{\mathrm{ey,l,p,b}} = \mathrm{P}^{\mathrm{S\_GEN}}_{\mathrm{ey,l,p,b}} \overline{p\_imp\_adj}_{\mathrm{ey,l.dp,db}} \qquad \text{AVI-39}
$$

GEN exports

$$
\mathrm{Q}^{\mathrm{EX\_GEN}}_{\mathrm{ey,l,p,b}} = \overline{\mathrm{dur}}_{\mathrm{l,gp,gb}} \frac{\overline{\mathrm{demand\_by\_agent}}_{\mathrm{y,ex,l,dp,db}}}{10^6} \qquad \text{AVI-40}
$$

$$
\mathrm{P}^{\mathrm{EX\_GEN}}_{\mathrm{ey,l,p,b}} = \mathrm{P}^{\mathrm{S\_GEN}}_{\mathrm{ey,l,p,b}} \overline{p\_exp\_adj}_{\mathrm{ey,l.dp,db}} \qquad \text{AVI-41}
$$

GEN final prices and quantities

$$
\mathrm{Q}^{\mathrm{Q\_GEN}}_{\mathrm{ey,l,p,b}} = \mathrm{Q}^{\mathrm{S\_GEN}}_{\mathrm{ey,l,p,b}} + \mathrm{Q}^{\mathrm{M\_GEN}}_{\mathrm{ey,l,p,b}} - \mathrm{Q}^{\mathrm{EX\_GEN}}_{\mathrm{ey,l,p,b}} \qquad \text{AVI-42}
$$

$$
\begin{aligned}
&(1 + s\_lump\_sum_{ey}) \mathrm{P}^{\mathrm{Q_{GEN}}}_{\mathrm{ey,l,p,b}} \mathrm{Q}^{\mathrm{Q_{GEN}}}_{\mathrm{ey,l,p,b}} = \\
&+ \bar{tx}^{Pdct\_GEN}_{ey,\mathrm{l,p,b},t} \sum_{t} \left(\sum_{gne} \mathrm{Q}^{II\_GNE\_GEN\_tech}_{\mathrm{ey,gne,l,p,b,t}} P^{Q}_{ey,gne} + \sum_{dp,db} \mathrm{Q}^{II\_GEN\_GEN\_tech}_{\mathrm{ey,l,dp,db,gp,gb,t}} \mathrm{P}^{Q\_GEN}_{\mathrm{ey,l,p,b}} \right. \\
&\qquad \left. + \mathrm{Q}^{II\_TDeO\_GEN\_tech}_{\mathrm{ey,l,p,b,t}} P^{TDeO}_{ey} \right) \\
&+ (1 + \bar{tx}^{sc\_GEN}_{ey,sne,pf=Labor})(1 - \mathrm{sc\_subisidy}_{ey}) P_{ey,pf=Labor} \mathrm{Q}^{pf\_GEN\_tech}_{\mathrm{ey,pf=Labor,l,p,b,t}} \\
&\qquad + P_{ey,pf=Capital} \mathrm{Q}^{pf\_GEN\_tech}_{\mathrm{ey,pf=Capital,l,p,b,t}} \\
&+ \sum_{pollut} \sum_{t,f} \left(\frac{\mathrm{PGEN}_{\mathrm{ey,t,f,l,p,b}}}{10^6} \overline{\mathrm{dur}}_{\mathrm{l,p,b}} \overline{emiss\ rate}^{pollut\_GEN}_{ey,t,f,pollut} \bar{p}^{pollut}_{ey,pollut} \right)
\end{aligned} \qquad \text{AVI-43}
$$

$$
\begin{aligned}
+\overline{\mathrm{tx}}^{\mathrm{Pdction\_GEN}}_{\mathrm{l,gp,gb}} + \mathrm{P}^{\mathrm{M\_GEN}}_{\mathrm{ey,l,p,b}}\mathrm{Q}^{\mathrm{M\_GEN}}_{\mathrm{ey,l,p,b}} - \left(1 + \overline{tx}^{Pdct}_{ey,Exp}\right)\mathrm{P}^{\mathrm{EX\_GEN}}_{\mathrm{ey,l,p,b}}\mathrm{Q}^{EX\_GEN}_{\mathrm{ey,l,p,b}} \\
- \sum_{t} \overline{emiss\_allow}_{ey,t,l,p,b} + \mathrm{Mkt\_Surplus}_{\mathrm{y,l,p,b}}
\end{aligned}
$$

Fuel price

$$
\mathrm{P}^{\mathrm{FUEL}}_{\mathrm{ey,t,f}} = \bar{\mathrm{p}}^{\mathrm{fuel}}_{\mathrm{y,p,t,f}} \frac{P^{Q}_{ey,gne}}{\bar{p}^{Q}_{ey,gne}} \tag{AVI-44}
$$

Bottom-up MCP optimal conditions:

Equations acquired from Annex IV, section AIV.4

$$
\begin{aligned}
&\left[\frac{\bar{\eta}_{\mathrm{y,l,t}}\ \mathrm{P}^{\mathrm{FUEL}}_{\mathrm{ey,t,f}}\ \overline{\mathrm{dur}}_{\mathrm{l,p,b}}}{10^6} + \sum_{pollut} \frac{\overline{emiss\ rate}^{pollut\_GEN}_{ey,t,f,pollut}\ \bar{p}^{pollut}_{ey,pollut}\overline{\mathrm{dur}}_{\mathrm{l,p,b}}}{10^6}\right. \\
&\qquad \left. + \frac{\overline{\mathrm{oem\_vom}}_{\mathrm{y,t}}\overline{\mathrm{dur}}_{\mathrm{l,p,b}}}{10^6} - \frac{\overline{\mathrm{premium}}^{\mathrm{renew}}_{\mathrm{t,f}}\overline{\mathrm{dur}}_{\mathrm{l,p,b}}}{10^6}\right] \\
&-\lambda^{Dem}_{y,l,p,b}\left[-1 + (\overline{\mathrm{own\_cons}}) + \overline{\mathrm{loss}}_{\mathrm{y,l,p,b}}\right] - \left\{\lambda^{Hyd\_Res}_{y,l,p}\left[\overline{\mathrm{dur}}_{\mathrm{l,p,b}}\right]\right\}_{if\ t=Hyd\_Res,f=\mathrm{na}} \\
&- \left\{\lambda^{Pump_{eff}}_{y,l}\left[\overline{\mathrm{dur}}_{\mathrm{l,p,b}}\right]\right\}_{if\ t=Pump,f="na"} - \left\{\lambda^{Pump_{Max}}_{y,l}\left[\overline{\mathrm{dur}}_{\mathrm{l,p,b}}\right]\right\}_{if\ t=Pump,f="na"} \\
&-\left\{\lambda^{Hyd\_RoR}_{y,l,p}\left[\overline{\mathrm{ror\_inflows}}_{\mathrm{y,l,p}} - \mathrm{PGEN}_{\mathrm{y,Hyd\_RoR,na,l,p,b}}\overline{\mathrm{dur}}_{\mathrm{l,p,b}}\right]\right\}_{if\ t=Hyd\_RoR,f=\mathrm{na}} \\
&-\lambda^{Cap\_availability}_{\mathrm{y,t,f,l,p,b}}[1] - \left\{\mu^{F-G\_use}_{y,l,p,b}\left[1 - \overline{\mathrm{pctg}}^{\mathrm{foil\_on\_fg}}_{\mathrm{y,l}}\right]\right\}_{if\ t=F-G,f=Fuel-oil} \\
&- \left\{\mu^{F-G\_use}_{y,l,p,b}\left[-\overline{\mathrm{pctg}}^{\mathrm{foil\_on\_fg}}_{\mathrm{y,l}}\right]\right\}_{if\ t=F-G,f=Natural\_gas} - \left\{\mu^{Wind}_{y,l,p,b}[1]\right\}_{if\ t=Wind,f="na"} \\
&-\left\{\mu^{ORSR}_{y,l,p,b}[1]\right\}_{if\ t=ORSR,f="na"} = 0
\end{aligned}
\tag{AVI-45}
$$

$$
\perp\ \mathrm{PGEN}_{\mathrm{y,t,f,l,p,b}}
$$

$$
-\lambda^{Dem}_{y,l,p,b}\left[1 - \overline{\mathrm{loss}}_{\mathrm{y,l,p,b}}\right] - \lambda^{Pump_{eff}}_{y,l}\left[-\overline{\mathrm{eff}}^{\mathrm{Pump}}\right] = 0 \tag{AVI-46}
$$

$$
\perp\ \mathrm{PPUMPED}_{\mathrm{y,l,p,b}}
$$

$$
-\lambda^{Hyd_{Res}}_{y,l,p}[-1] - \lambda^{Hyd_{Res}}_{y,l,p-1}[+1] = 0 \tag{AVI-47}
$$

$$
\perp\ \mathrm{RES}_{\mathrm{y,l,p}}
$$

$$
\begin{aligned}
&\left[\frac{\left(\overline{\mathrm{oem}_{\mathrm{fom}}}^{\mathrm{labor}}_{\mathrm{y,l,t}} + \overline{\mathrm{oem}_{\mathrm{fom}}}^{\mathrm{sc}}_{\mathrm{y,l,t}} + \overline{\mathrm{oem}_{\mathrm{fom}}}^{\mathrm{equip}}_{\mathrm{y,l,t}}\right)}{10^3}\right] \\
&\qquad - \left\{\lambda^{Reserves}_{y,l}[-1]\right\}_{if\ t=non\ intermitent\ technology} \\
&- \left\{\mu^{Wind}_{y,l,p,b}\left[-\left(\frac{\overline{\mathrm{pgen}_{\mathrm{base_{year}}}}_{\mathrm{l,p,b,Wind}}}{\overline{\mathrm{cap}}_{\mathrm{Base\ year,l,Wind}}}\right)\right]\right\}_{if\ t=Wind} \\
&\qquad - \left\{\mu^{ORSR}_{y,l,p,b}\left[-\left(\frac{\overline{\mathrm{pgen}_{\mathrm{base_{year}}}}_{\mathrm{l,p,b,ORSR}}}{\overline{\mathrm{cap}}_{\mathrm{Base\ year,l,ORSR}}}\right)\right]\right\}_{if\ t=ORSR} \\
&-\mu^{TCap}_{y,l,t}[1] - \lambda^{Cap_{availability}}_{\mathrm{y,t,f,l,p,b}}\left[-\overline{\mathrm{availability}}_{\mathrm{y,l,t}}\overline{\mathrm{stochastic}_{\mathrm{adj_{term}}}}_{\mathrm{y,l,p,b,y}}\mathrm{TCAP}_{\mathrm{y,l,t}}\right] = 0
\end{aligned}
\tag{AVI-48}
$$

$$
\perp\ \mathrm{TCAP}_{\mathrm{y,l,t}}
$$

$$\left[\sum_{\substack{y'>y\\ y'<y+\text{life}_{\text{time}}}} \frac{\overline{\text{overn}_{\text{costs}}}_{y,t}\,\overline{\text{idc}}_{t}\,\overline{\text{crf}}_{t}}{10^{3}}\right] - \mu_{y,l,t}^{TCap}[-1] = 0 \tag{AVI-49}$$

$$\perp \quad \text{PINS}_{y,l,t}$$

$$\frac{\text{Q}_{\text{ey,l,p,b}}^{\text{QGEN}}10^{6}}{\overline{\text{dur}}_{\text{l,gp,gb}}} - \left(\sum_{\text{t,f}} \text{PGEN}_{\text{y,t,f,l,p,b}}\right) - \overline{\text{imp}}_{\text{y,l,p,b}} + \text{PPUMPED}_{\text{y,l,p,b}} + (\overline{\text{own}_{\text{cons}}})\left(\sum_{\text{t,f}} \text{PGEN}_{\text{y,t,f,l,p,b}}\right) \tag{AVI-50}$$

$$+\overline{\text{loss}}_{\text{y,l,p,b}}\left(\left(\sum_{\text{t,f}} \text{PGEN}_{\text{y,t,f,l,p,b}}\right) + \overline{\text{imp}}_{\text{y,l,p,b}} + \overline{\text{exp}}_{\text{y,l,p,b}} - \text{PPUMPED}_{\text{y,l,p,b}}\right) \leq 0$$

$$\perp \quad \lambda_{y,l,p,b}^{Dem} \leq 0$$

$$\left(\sum_{\text{b}} \text{PGEN}_{\text{y,Hyd,na,l,p,b}}\right) - \text{RES}_{\text{y,l,p}} + \text{RES}_{\text{y,l,p+1}} - \overline{\text{inflows}}_{\text{y,l,p}} \leq 0 \tag{AVI-51}$$

$$\perp \quad \lambda_{y,l,p}^{Hyd\_res} \leq 0$$

$$\overline{\text{ror}_{\text{inflows}}}_{\text{y,l,p}} - \text{PGEN}_{\text{y,Hyd}_{\text{RoR}}\text{,na,l,p,b}}\overline{\text{dur}}_{\text{l,p,b}} \leq 0 \tag{AVI-52}$$

$$\perp \quad \lambda_{y,l,p}^{Hyd\_RoR} \leq 0$$

$$\left(\sum_{\text{p,b}} \text{PGEN}_{\text{y,Pump,na,l,p,b}}\overline{\text{dur}}_{\text{l,p,b}}\right) - \text{PPUMPED}_{\text{y,l,p,b}}\overline{\text{eff}}^{\text{Pump}} \leq 0 \tag{AVI-53}$$

$$\perp \quad \lambda_{y,l}^{Pump\_eff} \leq 0$$

$$\sum_{\text{p,b}} \text{PGEN}_{\text{y,Pump,na,l,p,b}}\overline{\text{dur}}_{\text{l,p,b}} - \overline{\text{res}_{\text{max}}}_{\text{y,l,Pump}} \leq 0 \tag{AVI-54}$$

$$\perp \quad \lambda_{y,l}^{Pump\_Max} \leq 0$$

$$\overline{\text{non}_{\text{intt}_{\text{coverage}}}}\max_{\text{p,b}}\left(\overline{\text{demand}}_{\text{y,l,p,b}}\right) - \sum_{\text{t}_{\text{non}_{\text{intt}}}} \text{TCAP}_{\text{y,l,t}} \leq 0 \tag{AVI-55}$$

$$\perp \quad \lambda_{y,l}^{Reserves} \leq 0$$

$$\text{PGEN}_{\text{y,t,f,l,p,b}} - \overline{\text{availability}}_{\text{y,l,t}}\overline{\text{stochastic}_{\text{adj}_{\text{term}}}}_{\text{y,l,p,b,y}}\text{TCAP}_{\text{y,l,t}} \leq 0 \tag{AVI-56}$$

$$\perp \quad \lambda_{y,l,t}^{Cap\_Availability} \leq 0$$

$$\text{PGEN}_{\text{y,F-G,Fuel-oil,l,p,b}} - \overline{\text{pctg}}_{\text{y,l}}^{\text{foil}_{\text{on}_{\text{fg}}}}\left(\sum_{\text{f}} \text{PGEN}_{\text{y,F-G,f,l,p,b}}\right) \leq 0 \tag{AVI-57}$$

$$\perp \quad \mu_{y,l,p,b}^{F-G\_use} \leq 0$$

$$\text{PGEN}_{\text{y,Wind,na,l,p,b}} - \overline{\text{pgen}_{\text{base}_{\text{year}}}}_{\text{l,p,b,Wind}}\left(\frac{\text{TCAP}_{\text{y,l,Wind}}}{\overline{\text{cap}}_{\text{Base year,l,Wind}}}\right) \leq 0 \tag{AVI-58}$$

$$\perp \quad \mu_{y,l,p,b}^{Wind} \leq 0$$

$$\text{PGEN}_{\text{y,ORSR,na,l,p,b}} - \overline{\text{pgen}_{\text{base}_{\text{year}}}}_{\text{l,p,b,ORSR}}\left(\frac{\text{TCAP}_{\text{y,l,ORSR}}}{\overline{\text{cap}}_{\text{Base year,l,ORSR}}}\right) \leq 0 \tag{AVI-59}$$

$$\perp \quad \mu_{y,l,p,b}^{ORSR} \leq 0$$

$$\mathrm{TCAP}_{\mathrm{y,l,t}} - \overline{\mathrm{cap}}_{\mathrm{y,l,t}} - \sum_{\substack{\mathrm{y'\leq y} \\ \mathrm{y`\geq y-life_{time}}}} \mathrm{PINS}_{\mathrm{y',l,t}} \leq 0 \qquad \text{AVI-60}$$

$$\perp \quad \mu_{y,l,t}^{TCap} \leq 0$$

Government:

Government income

$$Y_{ey}^{G} = \sum_{\mathrm{pf}} \mathrm{P}_{\mathrm{ey,pf}} \bar{\mathrm{q}}_{\mathrm{ey,pf}}^{\mathrm{G}} + \overline{\mathrm{transf}}_{ey}^{Ext-G} + \mathrm{Y}_{ey}^{TAX} \qquad ,\forall \mathrm{ey} \qquad \text{AVI-61}$$

Government expenditure

$$\begin{aligned}
\mathrm{E}_{ey}^{G} = {} & \\
& \sum_{\mathrm{gne}} \left(1 + \bar{\mathrm{tx}}_{ey}^{G}\right) \mathrm{P}_{\mathrm{ey,gne}}^{\mathrm{Q}} \bar{\mathrm{q}}_{\mathrm{ey,gne}}^{\mathrm{G}} + \left(1 + \bar{\mathrm{tx}}_{ey}^{G}\right) \mathrm{P}_{ey}^{\mathrm{Q\_TDeO}} \bar{\mathrm{q}}_{ey}^{\mathrm{G\_TDeO}} + \sum_{\mathrm{l,p,b}} \left(1 + \bar{\mathrm{tx}}_{ey}^{G}\right) \mathrm{P}_{\mathrm{ey,l,p,b}}^{\mathrm{Q\_GEN}} \bar{\mathrm{q}}_{\mathrm{ey,l,p,b}}^{\mathrm{G\_GEN}} \\
& + \overline{\mathrm{transf}}_{ey}^{\mathrm{G-H}} \\
& + \overline{\mathrm{psc}}_{ey}^{H} \Bigg(\sum_{sne} \big(\bar{tx}_{ey,sne,pf=Labor}^{SC\_SNE} - \mathrm{sc\_subsidy}_{ey} \\
& - \bar{tx}_{ey,sne,pf=Labor}^{SC\_SNE} \mathrm{sc\_subsidy}_{ey} \big) P_{ey,pf=Labor} Q_{ey,pf=Labor,sne}^{pf\_SNE} \\
& + \big(\bar{tx}_{ey,sne,pf=Labor}^{SC\_TDeO} - \mathrm{sc\_subsidy}_{ey} \\
& - \bar{tx}_{ey,sne,pf=Labor}^{SC\_TDeO} \mathrm{sc\_subsidy}_{ey} \big) P_{ey,pf=Labor} Q_{ey,pf=Labor}^{pf\_TDeO} \\
& + \sum_{l,p,b,t} \big(\bar{tx}_{ey,sne,pf=Labor}^{SC\_GEN} - \mathrm{sc\_subsidy}_{ey} \\
& - \bar{tx}_{ey,sne,pf=Labor}^{SC\_GEN} \mathrm{sc\_subsidy}_{ey} \big) P_{ey,pf=Labor} Q_{ey,pf=Labor,l,p,b,t}^{pf\_GEN\_tech} \Bigg) \\
& + \sum_{sne} \overline{transf}_{ey,sne}^{G\_sne} + \sum_{l,gp,gb} \overline{transf}_{ey,l,gp,gb}^{G\_GEN} \\
& + \sum_{t,l,gp,gb} \overline{emiss\_allow}_{ey,t,l,gp,gb} + \overline{\mathrm{transf}}_{ey}^{\mathrm{G\_TDeO}} \qquad ,\forall \mathrm{ey}
\end{aligned} \qquad \text{AVI-62}$$

Government savings

$$\mathrm{S}_{ey}^{G} = \mathrm{Y}_{ey}^{G} - \mathrm{E}_{ey}^{G} \qquad ,\forall \mathrm{ey} \qquad \text{AVI-63}$$

Government tax income

$$\begin{aligned}
\mathrm{Y}_{ey}^{TAX} = {} & \sum_{\mathrm{sne}} \Big(\bar{tx}_{ey,sne,pf=Labor}^{SC_{SNE}} - \mathrm{sc}_{\mathrm{subsidy}_{ey}} \\
& \qquad - \bar{tx}_{ey,sne,pf=Labor}^{SC_{SNE}} \mathrm{sc}_{\mathrm{subsidy}_{ey}} \Big) \mathrm{P}_{\mathrm{ey,pf=Labor}} \mathrm{Q}_{\mathrm{ey,pf=Labor,sne}}^{\mathrm{pf_{SNE}}} \\
& + \big(\bar{tx}_{ey,sne,pf=Labor}^{SC\_TDeO} - \mathrm{sc\_subsidy}_{ey} \\
& \qquad - \bar{tx}_{ey,sne,pf=Labor}^{SC\_TDeO} \mathrm{sc\_subsidy}_{ey} \big) \mathrm{P}_{\mathrm{ey,pf=Labor}} \mathrm{Q}_{\mathrm{ey,pf=Labor}}^{\mathrm{pf\_TDeO}} \\
& + \sum_{\mathrm{l,p,b,t}} \Big(\bar{tx}_{ey,sne,pf=Labor}^{SC_{GEN}} - \mathrm{sc}_{\mathrm{subsidy}_{ey}} \\
& \qquad - \bar{tx}_{ey,sne,pf=Labor}^{SC_{GEN}} \mathrm{sc}_{\mathrm{subsidy}_{ey}} \Big) \mathrm{P}_{\mathrm{ey,pf=Labor}} \mathrm{Q}_{\mathrm{ey,pf=Labor,l,p,b,t}}^{\mathrm{pf_{tech}}}
\end{aligned} \qquad \text{AVI-64}$$

$$+\sum_{\mathrm{sne,gne}} \overline{\mathrm{tx}}_{\mathrm{sne}}^{\mathrm{Pdct}} \mathrm{P}_{\mathrm{ey,gne}}^{\mathrm{Q}} \mathrm{Q}_{\mathrm{ey,gne,sne}}^{\mathrm{II}} + \sum_{\mathrm{gne}} \overline{\mathrm{tx}}^{\mathrm{Pdct\_TDeO}} \mathrm{P}_{\mathrm{ey,gne}}^{\mathrm{Q}} \mathrm{Q}_{\mathrm{ey,gne}}^{\mathrm{II\_GNE\_TDeO}}$$

$$+\sum_{\mathrm{sne}} \overline{\mathrm{tx}}_{\mathrm{sne}}^{\mathrm{Pdct}} \mathrm{P}_{ey}^{\mathrm{Q\_TDeO}} \mathrm{Q}_{\mathrm{ey,sne}}^{\mathrm{II\_TDeO\_SNE}}$$

$$+\sum_{\mathrm{l,p,b,t,gne}} \overline{\mathrm{tx}}_{\mathrm{l,p,b,t}}^{\mathrm{Pdct\_GEN}} \mathrm{P}_{ey,gne}^{\mathrm{Q}} \mathrm{Q}_{\mathrm{ey,gne,l,p,b,t}}^{\mathrm{II\_GNE\_GEN\_tech}} + \sum_{\mathrm{sne}} \overline{\mathrm{tx}}_{\mathrm{sne}}^{\mathrm{Pdct}} \mathrm{P}_{ey}^{\mathrm{Q\_TDeO}} \mathrm{Q}_{\mathrm{ey,sne}}^{\mathrm{II\_TDeO\_SNE}}$$

$$+\overline{\mathrm{tx}}^{\mathrm{Pdct\_TDeO}} \mathrm{P}_{ey}^{\mathrm{Q\_TDeO}} \mathrm{Q}_{ey}^{\mathrm{II\_TDeO\_TDeO}} + \sum_{\mathrm{l,p,b,t}} \overline{\mathrm{tx}}_{\mathrm{l,p,b,t}}^{\mathrm{Pdct\_GEN}} \mathrm{P}_{ey}^{\mathrm{Q\_TDeO}} \mathrm{Q}_{\mathrm{ey,l,p,b,t}}^{\mathrm{II\_TDeO\_GEN\_tech}}$$

$$+\sum_{\mathrm{sne,l,p,b}} \overline{\mathrm{tx}}_{\mathrm{sne}}^{\mathrm{Pdct}} \mathrm{P}_{\mathrm{ey,l,p,b}}^{\mathrm{Q\_GEN}} \mathrm{Q}_{\mathrm{ey,l,p,b,sne}}^{\mathrm{II\_GEN\_SNE}} + \sum_{\mathrm{l,dp,db}} \overline{\mathrm{tx}}^{\mathrm{Pdct\_TDeO}} \mathrm{P}_{\mathrm{ey,l,dp,db}}^{\mathrm{Q\_GEN}} \mathrm{Q}_{\mathrm{ey,l,gp,gb}}^{\mathrm{II\_GEN\_TDeO}}$$

$$+\sum_{\mathrm{l,gp,gb,t,dp,db}} \overline{\mathrm{tx}}_{\mathrm{l,gp,gb,t}}^{\mathrm{Pdct\_GEN}} \mathrm{P}_{\mathrm{ey,l,dp,db}}^{\mathrm{Q\_GEN}} \mathrm{Q}_{\mathrm{ey,l,dp,db,gp,gb,t}}^{\mathrm{II\_GEN\_GEN\_tech}} + \sum_{\mathrm{sne}} \overline{\mathrm{tx}}_{\mathrm{sne}}^{\mathrm{Pdction}}$$

$$+\overline{\mathrm{tx}}^{\mathrm{Pdction\_TDeO}} + \sum_{\mathrm{l,p,b}} \overline{\mathrm{tx}}_{\mathrm{l,gp,gb}}^{\mathrm{Pdction\_GEN}}$$

$$+\sum_{\mathrm{gne}} \overline{\mathrm{tx}}_{\mathrm{Exp}}^{\mathrm{Pdct}} \overline{\mathrm{p}}_{\mathrm{ey,gne}}^{\mathrm{EX}} \mathrm{Q}_{\mathrm{ey,gne}}^{\mathrm{EX}} + \sum_{\mathrm{l,p,b}} \overline{\mathrm{tx}}_{\mathrm{Exp}}^{\mathrm{Pdct}} \overline{\mathrm{p}}_{\mathrm{ey,l,gp,gb}}^{\mathrm{EX\_GEN}} \overline{\mathrm{q}}_{\mathrm{ey,l,gp,gb}}^{\mathrm{EX\_GEN}} + \sum_{\mathrm{gne}} \overline{\mathrm{tx}}^{\mathrm{H}} \mathrm{P}_{\mathrm{ey,gne}}^{\mathrm{Q}} \mathrm{Q}_{\mathrm{ey,gne}}^{\mathrm{H}}$$

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

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

$$\sum_{sne,pollut} \left(\overline{emıss\ rate}_{ey,sne,pollut}^{pollut\_sne} \bar{p}_{ey,pollut}^{pollut} Q_{ey,sne}^{S}\right)$$

$$+\sum_{pollut} \left(\overline{emıss\ rate}_{ey,pollut}^{pollut\_TDeO} \bar{p}_{ey,pollut}^{pollut} Q_{ey}^{S\_TDeO}\right)$$

$$+\sum_{l,b,p} \sum_{pollut} \sum_{t,f} \left(\overline{emıss\ rate}_{ey,t,f,pollut}^{pollut_{GEN}} \bar{p}_{ey,pollut}^{pollut} Q_{ey,l,p,b,t}^{S_{GEN_{tech}}}\right)$$

$$+\sum_{l,p,b} s\_lump\_sum_{ey} \mathrm{P}_{\mathrm{ey,l,p,b}}^{\mathrm{Q\_GEN}} \mathrm{Q}_{\mathrm{ey,l,p,b}}^{\mathrm{Q\_Gen}} + \sum_{gne} s\_lump\_sum_{ey} P_{ey,gne}^{Q} Q_{ey,gne}^{Q}$$

$$+ s\_lump\_sum_{ey} P_{ey}^{Q\_TDeO} Q_{ey}^{Q\_TDeO}$$

$$\perp \quad Y_{ey}^{TAX}$$

Savings and Investments:

Total savings

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

External savings

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

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$$- \sum_{\mathrm{l,gp,gb}} \left(1 + \overline{\mathrm{tx}}_{\mathrm{ey,Exp}}^{\mathrm{Pdct}}\right) \overline{\mathrm{p}}_{\mathrm{ey,l,gp,gb}}^{\mathrm{EX\_elect}} \overline{\mathrm{q}}_{\mathrm{ey,l,gp,gb}}^{\mathrm{EX\_elect}} - \overline{\mathrm{transf}}_{ey}^{\mathrm{Ext-G}} - \overline{\mathrm{transf}}_{ey}^{\mathrm{Ext-H}}$$

$$- \overline{\mathrm{transf}}_{ey}^{\mathrm{Ext-K}} \quad , \forall \mathrm{ey}$$

Investments

AVI-67

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

Market clearing conditions:

Production factors market clearing

$$\sum_{\mathrm{sne}} \mathrm{Q}_{\mathrm{ey,pf,sne}} + \mathrm{Q}^{\mathrm{pf\_TDeO}}_{\mathrm{ey,pf}} + \sum_{\mathrm{l,gp,gb,t}} \mathrm{Q}^{\mathrm{pf\_tech}}_{\mathrm{ey,pf,l,gp,gb,t}} + \left(\sum_{\mathrm{l,gp,gb}} \frac{\mathrm{Mkt\_Surplus}_{\mathrm{y,l,gp,gb}}}{P_{ey,pf}} \right)_{if\ pf=Capital} \leq \bar{\mathrm{q}}^{\mathrm{H}}_{\mathrm{ey,pf}} + \bar{\mathrm{q}}^{\mathrm{G}}_{\mathrm{ey,pf}} \perp \mathrm{P}_{\mathrm{ey,pf}} \quad , \forall \mathrm{ey, pf} \tag{AVI-68}$$

Non-electricity final goods market clearing

$$\mathrm{Q}^{\mathrm{H}}_{\mathrm{ey,gne}} + \bar{\mathrm{q}}^{\mathrm{G}}_{\mathrm{ey,gne}} + \sum_{\mathrm{sne}} \mathrm{Q}^{\mathrm{II}}_{\mathrm{ey,gne,sne}} + \mathrm{Q}^{\mathrm{II\_GNE\_TDeO}}_{\mathrm{ey,gne}} + \sum_{\mathrm{l,p,b,t}} \mathrm{Q}^{\mathrm{II\_GNE\_GEN\_tech}}_{\mathrm{ey,gne,l,p,b,t}} + \mathrm{Q}^{\mathrm{I}}_{\mathrm{ey,gne}} \leq \mathrm{Q}^{\mathrm{Q}}_{\mathrm{ey,gne}} \quad \perp \quad \mathrm{P}^{\mathrm{Q}}_{\mathrm{ey,gne}} \quad , \forall \mathrm{ey, gne} \tag{AVI-69}$$

GEN final goods market clearing

$$\mathrm{Q}^{\mathrm{H\_GEN}}_{\mathrm{ey,l,p,b}} + \bar{\mathrm{q}}^{\mathrm{G\_elec}}_{\mathrm{ey,l,p,b}} + \sum_{\mathrm{sne}} \mathrm{Q}^{\mathrm{II\_GEN\_SNE}}_{\mathrm{ey,l,p,b,sne}} + \mathrm{Q}^{\mathrm{II\_GEN\_TDeO}}_{\mathrm{ey,l,p,b}} + \sum_{\mathrm{gp,gb,t}} \mathrm{Q}^{\mathrm{II\_GEN\_GEN\_tech}}_{\mathrm{ey,l,p,b,gp,gb,t}} \leq \mathrm{Q}^{\mathrm{Q_{GEN}}}_{\mathrm{ey,l,p,b}} \quad \perp \quad \mathrm{P}^{\mathrm{Q_{GEN}}}_{\mathrm{ey,l,p,b}} \quad , \forall \mathrm{ey, l, p, b} \tag{AVI-70}$$

TD&O final goods market clearing

$$\mathrm{Q}^{\mathrm{H\_TDeO}}_{ey} + \bar{\mathrm{q}}^{\mathrm{G\_TDeO}}_{ey} + \sum_{\mathrm{sne}} \mathrm{Q}^{\mathrm{II\_TDeO\_SNE}}_{\mathrm{ey,sne}} + \mathrm{Q}^{\mathrm{II\_TDeO\_TDeO}}_{ey} + \sum_{\mathrm{l,p,b,t}} \mathrm{Q}^{\mathrm{II\_TDeO\_GEN\_tech}}_{\mathrm{ey,l,p,b,t}} \leq \mathrm{Q}^{\mathrm{Q\_TDeO}}_{ey} \quad \perp \quad \mathrm{P}^{\mathrm{Q\_TDeO}}_{ey} \quad , \forall \mathrm{ey} \tag{AVI-71}$$

Investments-savings identity

$$\mathrm{I}_{ey} = \mathrm{S}_{ey} \quad , \forall \mathrm{ey} \tag{AVI-72}$$

Consumer Price Index (model numeraire):

$$\mathrm{CPI} = \sum_{gne} \bar{\mu}^{Q}_{gne} \mathrm{P}^{\mathrm{Q}}_{\mathrm{ey,gne}} + \sum_{l,p,b} \bar{\mu}^{Q\_GEN}_{gne} \mathrm{P}^{Q\_GEN}_{\mathrm{ey,l,p,b}} + \bar{\mu}^{Q\_TDeO} \mathrm{P}^{\mathrm{Q\_TDeO}}_{ey} \qquad , \forall \mathrm{ey, gne} \tag{AVI-73}$$

Case study equations:

Environmental tax income

$$\begin{aligned} \mathrm{Y}^{Env\_tax}_{ey,pollut} = {} & \\ & \sum_{gne} \left(\overline{emiss\ rate}^{pollut_{H_{gne}}}_{ey,gne,pollut} \bar{p}^{pollut}_{ey,pollut} Q^{H}_{ey,gne} \right) \\ & + \left(\overline{emiss\ rate}^{pollut_{H_{TDeO}}}_{ey,pollut} \bar{p}^{pollut}_{ey,pollut} Q^{H_{TDeO}}_{ey} \right) \\ & + \sum_{l,p,b} \left(\overline{emiss\ rate}^{pollut_{H_{GEN}}}_{ey,l,p,b,pollut} \bar{p}^{pollut}_{ey,pollut} Q^{H_{GEN}}_{ey,l,p,b} \right) \\ & + \sum_{sne} \left(\overline{emiss\ rate}^{pollut\_sne}_{ey,sne,pollut} \bar{p}^{pollut}_{ey,pollut} Q^{S}_{ey,sne} \right) \\ & + \overline{emiss\ rate}^{pollut\_TDeO}_{ey,pollut} \bar{p}^{pollut}_{ey,pollut} Q^{S\_TDeO}_{ey} \end{aligned} \tag{AVI-74}$$

$$+\sum_{l,b,p}\sum_{t,f}\left(\overline{emiss\ rate}^{pollut_{GEN}}_{ey,t,f,pollut}\bar{p}^{pollut}_{ey,pollut}Q^{S_{GEN_{tech}}}_{ey,l,p,b,t}\right)$$

Social contributions subsidy

$$\text{sc\_subsidy}_{ey}=\sum_{pollut}\mathrm{Y}^{Env\_tax}_{ey,pollut}\,/$$

$$\left(\begin{array}{c}\displaystyle\sum_{sne}\left(1+\bar{tx}^{SC_{SNE}}_{ey,sne,pf=Labor}\right)P_{ey,pf=Labor}Q^{pf_{SNE}}_{ey,pf=Labor,sne}\\ +\left(1+\bar{tx}^{SC_{TDeO}}_{ey,sne,pf=Labor}\right)P_{ey,pf=Labor}Q^{pf_{TDeO}}_{ey,pf=Labor}\\ \displaystyle+\sum_{l,p,b,t}\left(1+\bar{tx}^{SC\_GEN}_{ey,sne,pf=Labor}\right)P_{ey,pf=Labor}Q^{pf\_GEN\_tech}_{ey,pf=Labor,l,p,b,t}\end{array}\right) \qquad \text{AVI-75}$$

Production sectors subsidy

$$\text{s\_lump\_sum}_{ey}=\sum_{pollut}\mathrm{Y}^{Env\_tax}_{ey,pollut}$$

$$/\left(\sum_{gne}P^{Q}_{ey,gne}Q^{Q}_{ey,gne}+P^{Q\_TDeO}_{ey}Q^{Q\_TDeO}_{ey}+\sum_{l,p,b}\mathrm{P}^{\mathrm{Q\_GEN}}_{\mathrm{ey,l,p,b}}\mathrm{Q}^{\mathrm{Q\_Gen}}_{\mathrm{ey,l,p,b}}\right) \qquad \text{AVI-76}$$