



# Electricity load level detail in computational general equilibrium – part II – welfare impacts of a demand response program



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## ABSTRACT

Demand Response (DR) programs send time-based signals to electricity consumers so that they may shift or reduce their loads to better adjust to the system requirements, thus creating interesting benefits for power systems. However, the assessment of these benefits is quite challenging, since it requires combining features from bottom-up and computable general equilibrium (CGE) models. This paper assesses the impacts of a DR program in Spain using a CGE model which includes both technological and temporal disaggregation. The model is able to account for the indirect effects characteristic of CGE models while also mimicking the detailed behavior of the electricity operation and investment available before only in bottom-up detailed models. Our results show clearly the advantages of using this approach for this type of policies.

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## 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.<sup>1</sup>

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 and Sergici, 2010](#)). Consumers are responding to them basically shifting their demand from the time in which electricity 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.

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<sup>1</sup> 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.

Several attempts have been made at assessing the costs and benefits of these programs (see e.g. [Conchado and 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 and Reilly, 2004](#); [Paltsev et al., 2005](#); [Sue Wing, 2008](#)), or even hybridizing bottom-up and top-down models (e.g. [Böhringer and Rutherford, 2008](#); [Proença and St. Aubyn, 2012](#)), 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. Part I of this paper ([Rodríguez and Linares, 2014](#)) presented the first attempt to our knowledge at building temporal disaggregation into a CGE framework, while keeping technological detail.

In this companion paper we apply the CGE model developed, GEMED, to the assessment of 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,<sup>2</sup> and therefore, the better the evaluation of the policy effects.

Section 2 describes the improved CGE model, while Section 3 describes the assessment and how the DR program is modeled. Section 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 5 presents some conclusions and research extensions.

## 2. The CGE model: GEMED

GEMED is a static, open economy, CGE model applied to a single country. The algebraic formulation follows a system of non-linear inequalities in the Arrow-Debreu general equilibrium framework. The model is implemented in GAMS and uses the PATH solver to obtain a local optimal equilibrium point. The functional form and data requirements necessary to define the model are described shortly in this section. The description of the equations and a more exhaustive explanation of the model can be found in Annex I.

The model assumes two production factors, labor and capital, perfectly mobile across sectors and allocated according to a perfectly 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 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)<sup>3</sup> and one energy intensive sector (Transport).

The assumptions made in the model and described here and in Annex I are very much in line with the usual ones in CGE literature and small countries closure assumptions (e.g. [Shoven and Whalley, 1984](#); [Devarajan et al., 1986](#); [Robinson et al., 1999](#); [Paltsev et al., 2005](#); [Proença and St. Aubyn, 2012](#)).

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 [Rodríguez and Linares \(2014\)](#).

### 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 paper we chose to adopt a relatively simple network component (TD&O) description.<sup>4</sup> 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<sup>5</sup>) 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.

<sup>3</sup> 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 paper. More policy-oriented papers should consider a more exhaustive representation of production sectors according to the policy consequences to be evaluated.

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

<sup>5</sup> By location we refer to different, non-connected power systems within the same economic region (and therefore linked through economic macromagnitudes). It makes no sense to differentiate locations if connected to the same power system given that in that case electrons cannot be geographically traced. For the sake of clarity, we will not refer much to location detail in what follows, given that the focus of the paper is on the time-period detail.

<sup>2</sup> In related literature these are known as the macroeconomic rebound effect (e.g. [Herring and Sorrell, 2009](#)).

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