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An analytical approach to activating demand elasticity with a demand response mechanism

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ABSTRACT

The aim of this work is to demonstrate analytically the conditions under which activating the elasticity of consumer demand could benefit social welfare. We have developed an analytical equilibrium model to quantify the effect of deploying demand response on social welfare and energy trade. The novelty of this research is that it demonstrates the existence of an optimal area for the price signal in which demand response enhances social welfare. This optimal area is negatively correlated to the degree of competitiveness of generation technologies and the market size of the system. In particular, it should be noted that the value of unserved energy or energy reduction which the producers could lose from such a demand response scheme would limit its effectiveness. This constraint is even greater if energy trade between countries is limited. Finally, we have demonstrated scope for more aggressive demand response, when only considering the impact in terms of consumer surplus.

1. Introduction

The deployment of smart grids is seen as heralding a major change in electricity markets. One of the main considerations, presented as a necessary condition to benefit from this development, is to be able pilot demand or make it respond to price or market constraints (Chao, 2011). Setting aside any improvements in network management, consumer behaviour will have a key impact on uses and investment-planning in the midstream (networks) and the upstream (generation) (Strbac, 2008). The idea is to replace some of the heavy investment in infrastructure by a reduction in consumption. This could be done by consumers or another body (aggregators, suppliers, or distributors) on behalf of consumers. Experiments have shown that investing in smart-grid technology could be cheaper than heavier investments in infrastructure (Kema, 2012).

The main feature of electricity demand is its inelasticity (Stoft, 2002). Currently, most electricity consumers are captive in the short term. Industrial customers could be more volatile, but mainly in the long term (Lijesen, 2007; Patrick and Wolak, 2001). However, the aim of deploying smart grids and demand response (DR) schemes is to introduce short-term elasticity into some uses. In this way, issuing price signals to consumers will always reduce consumption.[2] The literature generally shows that demand is elastic when a dynamic tariff is introduced. However, the value of the elasticity varies depending on several factors, such as the period of consumption, household appliances, degree of deployment of smart-grid technologies, or the price differential between periods of consumption (Boisvert et al., 2004; Di Cosmo et al., 2014; Faruqui and Sergici, 2010). Several papers have studied the impact of dynamic pricing on consumers and markets design to remunerate curtailments. Chao (2011) has demonstrated that, in a perfect competitive market, remuneration of curtailment is equivalent to the difference between the retail rate and the real-time price should be optimal for welfare. Orans et al. (2010) show that a three-part tariff, including time-of-use, a fixed fee, and DR remuneration, is an efficient tool for providing consumers with an incentive to change their behaviour.

We draw on these papers using analytical equilibrium in interconnected markets to study the cases in which an increase in tariffs would reduce consumption without jeopardizing social welfare. We use a deterministic optimization model with supply functions (Ventosa et al., 2005). As in other papers (Stoft, 2002), we assume perfect competitive markets. Each producer bases its bids on its marginal costs, as in Woo (1990) and De Jonghe et al. (2011). However, to our

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[2] This result could be overcome by extending the rebound effect (Muratori et al., 2014).

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knowledge, only a few works have sought to analytically model the deployment of demand response in the context of interconnected electricity markets. Vespucci et al. (2013) is the model closest to ours. A large part of their analysis focuses on the transformation of their optimization problem into a linear one, as electric supply and demand functions are discontinuous.They also demonstrate, with application data, that a dominant firm always has an incentive to use market power to achieve higher profit targets. Our model differs from theirs on two points. Firstly, we compute theoretical equilibriums in the context of two interconnected markets with several technologies in each market. Secondly, we introduce an analysis of demand response (DR) linked to the degree of the elasticity of consumer demand. Léautier (2014) has also studied, using an analytical approach, the impacts on welfare of switching from inelastic to elastic demand via the application of real-time pricing scheme.[3] Our analysis extends this work by addressing the effectiveness of demand response when several markets, using different generation technologies, are interconnected. It adds to this literature on considering the extent to which the effectiveness of a demand response should consider the system's interactions with foreign systems through the energy exchanges and the difference between the generation technologies mix.

In our research work, we focus on the effectiveness of deploying a demand response scheme. We may assume that widespread application of DR would have several impacts on system equilibrium. The main objective of this scheme is to make consumers sensitive to prices in the short run.[4] They could actively participate in managing system security, instead of relying only on supply management when the system is close to rationing. DR schemes offer consumers an incentive to adopt a degree of flexibility in their consumption. Each part of the electricity supply chain would benefit from this flexibility, gaining in efficiency.

Deploying a mechanism of this sort would nevertheless have a high cost. Consumers need to adapt and modify their behaviour, switching from being captive and non-elastic to being genuinely elastic. It is worth noting that under a DR scheme, demand becomes elastic for a large range of consumers, independently of their own appliances. As several pilot schemes in the US have shown (Faruqui et al., 2009), the main gains are obviously achieved at peak hours. Demand for electrical heating or air conditioning are the main categories of consumption which could be managed under DR schemes. However, dynamic pricing gives a large share of consumers an incentive to reduce consumption, regardless of whether they own air conditioning, for example (Di Cosmo et al., 2014). Information technology, such as home displays, increases such effects, providing continuous information to customers on consumption and tariffs. The impact of DR schemes on price bids has been studied in the literature. DR is a key factor in making smart grids work because it allows efficient interaction between the segments of the electricity supply chain.[5] The literature has studied a variety of DR tools (Bergaentzlé et al., 2014; Faruqui and Sergici, 2010; Horowitz and Lave, 2014), going from the simplest mechanism which involves dividing periods of consumption into price blocks, in which the price increases in step with short-term system vulnerability (time-of-use or critical peak pricing), to more complex systems in which consumers respond to electricity prices in real time (real-time pricing). When several communications technologies are developed, load management of consumers by the supplier or the distribution system operator would allow a significant decrease in demand, higher than a reduction managed only by the consumer. All these tools imply an increase in electricity prices at times of high demand and lower prices at other times. It seems realistic to assume that activating DR will result in an increase in electricity prices in peak periods. As prices increase, some consumers could be worse off due to this increase (Horowitz and Lave, 2014). As the main gain from a DR scheme is a drop in peak-load demand, incentive prices or direct load control are used to make the volume effect greater than the price effect; in other words, decreasing electricity consumption compensates for increasing prices. This should be done by minimizing the impact on consumer utility,[6] as consumers must have incentives to participate in a DR scheme. We shall therefore study two economic indicators—social welfare and consumer surplus—to gauge the efficiency of the DR schemes.

In our paper, we model a system in which generators, integrated with suppliers or retailers, make bids (supply curves) to the system operator which maximizes the welfare balancing offer and demand. With SG technologies, consumers could become active on the market; thus, their demand function becomes elastic. In this environment, we start by analysing the way the structure of generating technologies could affect merit orders in different countries and potential trade between them. Our results show that the trade-off between producing locally and exporting energy depends on the opportunity cost of the energy and the overall efficiency of generating technologies. Then, we demonstrate that there is an optimal level for the price signal at which DR increases social welfare. We use computed equilibria from our initial analysis to show that this optimal level is negatively correlated to the degree of competitiveness of the generating technologies and the size of the market. The value which producers could lose due to unserved energy or energy reductions would limit the deployment of a scheme of this sort. Moreover, this constraint is greater if energy trade between countries is limited. However, the constraint is less acute if the considered system is cost-inefficient, with only limited connections with neighbouring systems.

The paper is divided into five sections. Following this introduction, Section 2 presents the assumptions used in modelling the analytical equilibriums and results of social-welfare analysis. Section 3 focuses on the effectiveness of DR with regard to consumer-surplus criteria. Section 4 analyses the sensitivity of the results to the elasticity of demand. Section 5 presents our conclusions.

2. A model for demand response

2.1. General assumptions

2.1.1. Trade between the systems

We shall assume there are two interconnected countries[7] ($n = 1{,}2$).[8] Each system operator balances total supply and demand, making allowance for possible trade between the countries. Such trade is limited by an interconnection capacity between country n and m, $Cap_{n,m}$, which has a price $P_{n,m}$ when capacity is saturated.

2.1.2. Generation technologies and supply

Each country is characterized by the presence of t generation technologies, $t = \{1\ldots\ k\}$. We assume perfect competition in both markets.[9]

3 Léautier (2014) applies his results to the French market. As marginal revenue of SG deployment is decreasing, current costs of marginal deployment of smart meters are too high compared to benefits. Thus, it should be not profitable to continue to install equipment for all consumers. Moreover, Crampes and Léautier (2015) have recently shown that under imperfect information, DR could reduce the welfare from the adjustment market as consumers could behave strategically.

4 Electricity consumers are recognized to be elastic only in the long run, even if in the short run, some of them can be partly elastic too. We also note that we make no distinction between residential and industrial consumers, who have different consumption profiles and would, in practice, react differently to an intensive DR scheme.

5 For instance, generators of conventional or intermittent energies could easily manage variations in their production and integrate renewable energies in the power system.

6 One of the main fields of research by suppliers is for ways of convincing consumers to participate in DR schemes. To gain consumer acceptance, DR schemes must minimize impact on both modern amenities and electricity bills.

7 The model could be enlarged to analyse more than two interconnected systems.

8 Index m is also used.

9 We disregard the strategic behaviour of producers by assuming that the merit order of a given system is the result of aggregating the marginal costs of available generation technologies. The model is a one-shot game with linear demand. To serve demand, all capacities are offered to the market through the aggregate supply function.