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Examining the benefits of load shedding strategies using a rolling-horizon stochastic mixed complementarity equilibrium model

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ABSTRACT

As a result of government policies increasing the amount of electricity generated from fluctuating renewable sources in many countries, the requirement for flexibility in the corresponding electricity systems increases. On the demand side, load shedding is one demand response mechanism contributing to an increased flexibility. Traditionally, load shedding was based on rather static or rotational strategies, whereby the system operator chooses the consumers for load shedding. However, ongoing technological developments provide the basis for smarter and more efficient load shedding strategies. We therefore examine the costs and strategies associated with such mechanisms by modelling an electricity market with different types of generators and consumers. Some consumers provide flexibility through load shedding only while others additionally have the ability to generate their own electricity. Focussing on the impacts of how and to whom consumers with own generation ability can supply electricity, the presence of market power and generator uncertainty, we propose a rolling horizon stochastic mixed complementarity equilibrium model, where the individual optimisation problems of each player are solved simultaneously and in equilibrium. We find that a non-static strategy reduces consumer costs while allowing consumers to provide own generation to the whole market results in minimal benefits. The presence of market power was found to increase costs to consumers.

1. Introduction

Many governments have adopted policies for expanding the use of renewable energy sources (RES) aimed at reducing greenhouse gas emissions. As a result of an increasing use particularly of fluctuating RES, such as wind and solar energy, the volatility of the system residual load will increase strongly leading to growing flexibility requirements (Bertsch, Growitsch, Lorenczik, & Nagl, 2016). In order to meet these requirements, electricity markets need to become more flexible. While traditionally, flexibility has been mainly provided by the supply side, demand side flexibility has gained increasing interest over the last decade and is expected to become increasingly important in the future (De Jonghe, Hobbs, & Belmans, 2012; Palensky & Dietrich, 2011). Kirby and Hirst (1999) as well as Chen, Li, Low, and Doyle (2010), for instance, describe the system benefits (mainly efficiency gains and cost reductions) of an increased demand side flexibility. In this context, Palensky and Dietrich (2011) distinguish between four categories of demand side management: energy efficiency, time of use, demand response and spinning reserve. Aimed at exploring market-based solutions to meet short-term flexibility requirements, we focus on the demand response category in this paper. Within the demand response category, Albadi and El-Saadany (2008) distinguish between load reduction/shedding, load shifting and consumer-owned, distributed self-generation, whereas Bayer (2014) distinguishes between reduction/shedding, shifting and increase of load. The majority of existing research concentrates on load shifting. However, empirical research findings suggest that consumers respond to higher prices by reducing electricity consumption during peak periods (Faruqui & Sergici, 2010), but that they do not necessarily shift their consumption to off-peak periods (Allcott, 2011; Di Cosmo, Lyons, & Nolan, 2014). We therefore focus on the examination of benefits of load shedding strategies in this paper. Consequently, we study the temporary short-term reduction of load in situations where the demand for electricity exceeds the supply capacity or where there is inadequate transmission capacity available to deliver sufficient electricity to the areas and consumers where it is needed.

Traditionally, load shedding involved strategies where the system operator chooses the consumers that must shed their load – mostly following a rather static or a rotational scheme. Under a static scheme, the system operator can shed load of specific consumers according to predefined conditions (e.g., sheddable

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capacity and corresponding price) laid down in a contract or according to predefined priorities of consumers (Calderaro, Galdi, Lattarulo, & Siano, 2010). Under a rotational scheme, the system operator can shed load in a specific part of the electricity network at a time, where the affected areas and consumers will change over time in order to ensure a fair burden sharing. While being a common event in many developing countries, load shedding, particularly the rotational scheme is rather a measure of last resort in developed countries today, used by the system operator to avoid a total blackout of the power system.

However, the increasing digitisation driven by ongoing developments in information and communication technology (ICT) enables the transformation of electricity distribution grids towards active distribution grids (Ruppert, Bertsch, & Fichtner, 2015; Woo et al., 2014) and provides the basis for smarter and more efficient (non-static) load shedding strategies. For instance, shedding load of a particular consumer would not need to result in a complete blackout for this consumer but could simply imply a partial load reduction ("brownout"). Such interruptible and curtailable electricity load programmes have also been reported and explored by others (Albadi & El-Saadany, 2008; C. R. Associates, 2005; U. D. of Energy, 2006; Faruqui, Hledik, & Sergici, 2010; Ströhle & Flath, 2016; Woo et al., 2014). In essence, while implying curtailments for some consumers, such approaches help avoid blackouts and therefore increase energy security on a system level. The European Energy Security Strategy (EC, 2014) and the European Directive on Security of Network and Information Systems (EC, 2016) both acknowledge the need for increasing energy system security and underline the relevance of such approaches, while at the same time highlighting the need for addressing these challenges in a competitive market environment.

Our focus in this paper is therefore to examine the potential costs and benefits of different strategies for load shedding as one set of instruments within the field of demand response. For this purpose, we assume a competitive electricity market with multiple generators and different types of consumers which can be distinguished according to their load shedding ability and costs. We also assume that some consumers provide flexibility to the market through load shedding only while others additionally have the ability to generate their own electricity by auxiliary power generation units (APUs). Moreover, we consider uncertain generator availability. In such an environment, we are particularly interested in exploring the following research questions:

1. What are the benefits of allowing consumers with own generation to provide generation to the whole market?
2. How do 'smart' (non-static) load shedding strategies compare with static and rotational load shedding schemes and how do they differ in terms of costs to consumers?
3. How does the presence/absence of market power affect costs to consumers?
4. What are the benefits of a stochastic planning approach over a deterministic one?

Demand response has been studied intensely in the literature (see e.g. reviews by Albadi & El-Saadany, 2008; Boßmann & Eser, 2016; DECC, 2012; Esther & Kumar, 2016; Haider, See, & Elmenreich, 2016; Hornby, Hurley, & Knight, 2011). Load shedding, in particular, has been investigated using heuristic techniques (Laghari, Mokhlis, Bakar, & Mohamad, 2013) as well as linear or nonlinear programming techniques (Subramanian, 1971). Wang and Billinton (2000), for instance, consider time-dependent, linear load shedding cost functions of different consumer types in an optimal load shedding approach. However, in order to explore the research questions set out above, most existing approaches are limited with respect to at least one of the following two characteristics:

- The load shedding cost functions are assumed to be linear.
- Load shedding is optimised from a central planning perspective using a single optimisation problem.

In relation to the first limitation, we wish to note that the costs associated with load shedding should not be assumed to increase linearly when the amount of load shedding is increased. Low amounts of lost load, for instance, may only lead to low-cost effects (e.g., reduced illumination) whereas higher amounts of lost load may induce much higher losses across different consumer types (Ruppert et al., 2015). In relation to the second limitation, a central planning optimisation does not take into account individual optimisation targets of different players. Hence, methods are needed that allow for the simultaneous consideration of multiple, individual optimisation problems (such as complementarity problems) and for the incorporation of consumer-specific, nonlinear load shedding cost functions. Moreover, with a view to our research questions, the methods should be able to consider market power, electricity generation by consumers and stochastic supply. Chen et al. (2010), for instance, use a game-theoretic equilibrium model with a quadratic load shedding cost function. The model by De Jonghe et al. (2012) is very similar. However, both do not take into account market power, APU generation or stochastic supply.

We therefore propose using a game-theoretic equilibrium model, namely a stochastic mixed complementarity problem (MCP) with quadratic load shedding cost functions, to analyse interactions of different players in a competitive electricity market. MCPs have been used to model various types of energy markets (Devine, Gabriel, & Moryadee, 2016; Egging, 2013; Gabriel, Zhuang, & Egging, 2009; Hobbs, 2001; Huppmann, 2013; Lynch & Devine, 2017). They allow the optimisation problems of multiple individual players to be solved simultaneously and in equilibrium by combining the Karush–Khun–Tucker (KKT) conditions for optimality of each of the players and connecting them via market clearing conditions. In addition, MCPs allow both primal variables (e.g., power generation) and dual variables (e.g., prices) to be constrained together (Gabriel, Conejo, Fuller, Hobbs, & Ruiz, 2012) while also allowing players with constrained optimisation problems to be modelled as either price-takers or price-makers, hence, incorporating market power into such models (Gabriel, Kiet, & Zhuang, 2005; Lee, 2016). Traditionally, price-makers have been modelled using simple linear demand curves ($Demand = A - B \times Price$). However, in this work, we model price-makers in a novel manner by combining a supply-demand equation with the KKT conditions of the consumers.

We apply the proposed stochastic MCP in the context of a case study based on data for Ireland. The players that we consider in the case study include different types of generators and consumers. The generators produce electricity to maximise their profits and may be price-takers or price-makers as described above. The consumers in our model choose how much of their load to shed in order to meet their demand at minimum costs and may differ in terms of their electricity demand profiles, their load shedding potential and cost functions and their ability to generate their own electricity. We consider consumers with the ability to generate electricity as *active* load shedding consumers and consumers without this ability as *passive* load shedding consumers. Note that, in reality, neither active nor passive consumers would usually decide themselves whether or not and when to shed any load. Rather, we assume that there will be an aggregator who acts on behalf of the consumers (Burger, Chaves-Ávila, Batlle, & Pérez-Arriaga, 2016; Ceseña, Good, & Mancarella, 2015; Good, Ellis, & Mancarella, 2017), with the objective of minimising their energy supply costs. For the model, however, this does not make a difference. Moreover, the market we model is one with a significant presence of smart meters, such as the Irish electricity market in future (Commission for Energy Regulation, 2014). These smart meters will allow con-

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