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Load-shift incentives for household demand response: Evaluation of hourly dynamic pricing and rebate schemes in a wind-based electricity system

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ABSTRACT

Applying a partial equilibrium model of the electricity market we analyse effects of exposing household electricity customers to retail products with variable pricing. Both short-term and long-term effects of exposing customers to hourly spot market prices and a simpler rebate scheme are analysed under scenarios with large shares of wind power in a Danish case study. Our results indicate strategies that could be favourable in ensuring high adoption of products and efficient response by households. We find that simple pricing schemes, though economically less efficient, could become important in an early phase to initialise the development of household demand response. At a later point, when long-term dynamics take effect, a larger effort should be made to shift consumers onto real-time rates, and an increased focus on overall adoption of variable pricing will be required. Another finding is that demand response under variable pricing makes wind power more valuable. These gains in value reduce the need for support, and could be redistributed in further support of demand response.

1. Introduction

Incentives for household electricity consumers to provide flexibility are increasingly being discussed to support the integration of intermittent renewable energies [1]. To do so, incentives need to be highly dynamic, and real-time pricing is frequently mentioned as providing highest economic benefits. Households may perceive dynamic pricing as complex and as potentially colliding with their preference for stability, predictability and low risk [2,3]. Because individual behaviour shapes household consumption [4], it will barely be planned ahead of time and will most often not be automated or remote controlled. Demand response in this segment may therefore face a dilemma in that the economically most efficient pricing schemes will be too complex for the majority of customers to become interested in or react upon. If schemes are simplified, on the other hand, they will generate far less economic benefits, especially in systems with large shares of renewable generation. In this paper we contribute to evaluating this trade-off between economic efficiency and product simplicity by determining the effect of a simple rebate scheme as compared to dynamic hourly pricing.

While our analysis builds on general economic principles, we derive results in a stylised Danish setting, to illustrate the interplay of demand response with large-scale development of intermittent production. With Danish energy policy aiming at a fossil-free electricity supply in 2035 [5], wind energy is going to play a major role in the future [6]. In 2020 electricity generation from wind energy should make up close to 50% of annual consumption [7]. The increasing volumes of wind power require sufficient flexible capacity to maintain a stable system, and with conventional power plants replaced by renewable generators, the Danish electricity system operator, amongst several other initiatives, aims at a better utilisation of demand-side flexibility [8]; though this still is subject to removing various barriers within the regulatory framework [9].

We focus on household consumption, because in this segment we expect the trade-off between efficiency and effectiveness of incentives to be most significant. It has been established that household consumers hold a technical potential to provide flexibility [10]. Several studies show that, when provided with economic incentives, they will utilise their potential and thus reveal some extent of elasticity towards short-term electricity prices (see Faruqui and Sergici [11] for an overview). For competitive retail markets it should be acknowledged, though, that consumers

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cannot be forced into specific schemes. They rather choose their pricing plans themselves and determine which products for demand response are going to be adopted.

Possible products have been discussed thoroughly [12] and may be categorised into price-based and volume-based schemes, depending on whether customers receive varying prices or are subject to direct constraints on their level of consumption [13]. Demand response of households without the use of automation will typically have to occur under price-based schemes. Here we can distinguish three major types of rate designs [14]: 1) time-of-use pricing, 2) critical event pricing, 3) real-time pricing. The first type consists of a mostly static pattern of prices that make it less efficient in a system based on wind power like the Danish one. The latter two are more dynamic schemes. In critical event pricing customers are subject to a significant price increase or rebate at specific times considered critical. With real-time pricing customers receive frequently updated price signals reflecting system cost. While all of these schemes provide an incentive for demand response, they differ in their theoretical economic potential and in how effective they will be in practice.

Real-time pricing is the ideal scheme from an economic point of view [15] and should be well suited in a dynamic environment with large fluctuations from wind power. Recent experience shows, however, that real-time prices work best with automated control and may be less applicable to manual response [16,17]. Comparisons of dynamic pricing studies also reveal that higher elasticities are achieved under critical event pricing or time-of-use schemes than under real-time pricing [18]. Schemes with higher economic potential tend to be more complex from a customer point of view [19] resulting in higher transaction costs [20], which in turn may reduce effectiveness by lowering adoption and response potential. Fig. 1 is an attempt to illustrate this trade-off by putting different types of pricing schemes into the two mentioned dimensions. So although real-time pricing in theory should be the best solution, it might not be in practice, when taking into account behavioural aspects of households like: response fatigue [21], risk aversion [22] and resistance to increasing transaction cost [23].

In this paper we evaluate the economic benefits of an electricity retail product for demand response that is less complex than real-time pricing. We therefore compare economic gains of switching customers from a flat rate to hourly pricing to those of switching customers to a rebate product that customers should be better able to foresee the implications of. For that purpose we

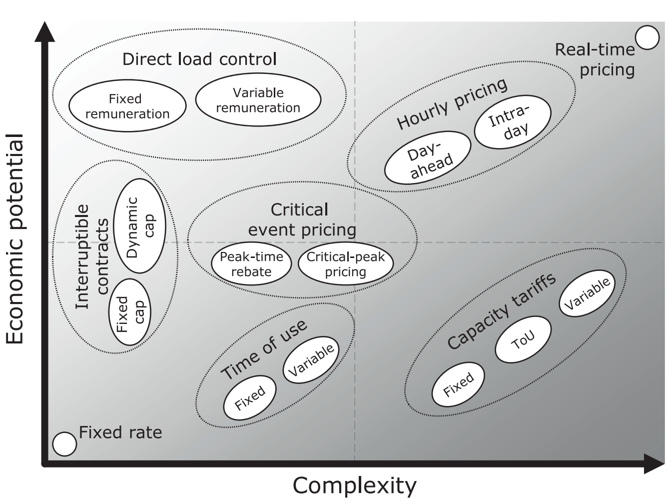

Fig. 1. Complexity and economic potential of different pricing schemes.

set up a partial equilibrium model of the electricity market based on hourly values (Section 2) and derive results for two different scenarios of wind production in a Danish setting (Section 3 presents the underlying case study assumptions). We then compare outcomes for the different retail price regimes (Sections 4 and 5).

As we will show in the following brief review of related work, elements of our study have been addressed in the literature previously. Economic analyses of demand response have been conducted in various studies and within different market and regulatory contexts (for an overview see Conchado and Linares [18]). Where we identify a gap and contribute with this paper is in economic benefit analyses of different retail pricing schemes including long-term dynamics in a setting with intermittent renewables. Based on such analyses we will be better able to evaluate the gap in economic benefit that we might have to accept in order to achieve effective incentives in terms of adoption and response levels.

A number of studies conduct their analysis in a static setting assuming the response has no impact on prices. Many of these works consider real-time or hourly pricing: e.g. analysing heating and cooling in Texas [24], household appliances in Ireland [25] and Germany [26,27] or storage-like loads under German [28] and Danish [29] conditions. Static prices simplify the analysis of different retail pricing structures, which might be the reason that besides real-time pricing also many analyses of simpler rate structures have been performed. Some of them study critical event pricing [30,31], but most works look into the effects of time-of-use rates from the perspective of utilities [32–34] or customers [35,36].

We choose an approach based on economic equilibrium modelling in order to account for the dynamic market impacts of demand response. After all the impact on prices and generation capacities has been one of the main arguments in favour of demand response. Even though many studies use a similar equilibrium approach, they do not necessarily take long-term dynamics into account. Such works acknowledge the price impact of the response, but keep supply capacities static. Analyses with a short-term focus have been carried out examining real-time or day-ahead pricing (e.g. in the US [37–39], the UK [40,41], Slovenia [42] or Denmark [43]), time-of-use and critical peak pricing [44,45] as well as incentive-based response schemes [46,47]. A short-term equilibrium approach provides a bit more insight into the market dynamics of demand response. To fully evaluate the impact of policies, however, the short-term approach should be accompanied by an analysis of the long-term equilibrium [48]. One particular formal equilibrium framework developed for demand response by Borenstein and Holland [49] has been applied several times in different variations, showing how real-time pricing and resulting response of elastic demand generates significant benefits even with limited elasticities, for example, for US electricity markets [50,51] and Norway [52]. A related approach has been developed and applied to four weeks of Danish wind and demand data [53].

Long-term models result in the construction of an electricity system with optimal generation capacities. Usually this neglects existing capacity in a market, assuming divestment from overcapacity. As long as the state of the system is not taken into account, the long-term equilibrium found remains somewhat theoretical. Energy system models take a step further. They require a high level of detail in representing the energy system often resulting in extensive computation requirements. Analyses have been carried out, for example, with a focus on demand response from residential appliances [54–56], heat pumps [57–59] or electric vehicles [60–62].

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