Energy Policy 123 (2018) 642–658

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Real-time pricing revisited: Demand flexibility in the presence of micro-generation

Chandra Kiran B. Krishnamurthy[a,b,*], Mattias Vesterberg[b,c], Herman Böök[d], Anders V. Lindfors[d], Rauli Svento[e]

[a] Department of Forest Economics, Swedish University of Agricultural Sciences (SLU), Umeå, Sweden
[b] Center for Environmental and Resource Economics, CERE, Umeå, Sweden
[c] Umeå School of Business and Economics (USBE), Department of Economics, Umeå University, Umeå, Sweden
[d] Finnish Meteorological Institute, Helsinki, Finland
[e] Department of Economics, Oulu Business School, Oulu University, Finland

ARTICLE INFO

JEL classification:
D12
Q41
C10

Keywords:
Real time electricity pricing
Energy demand
Renewable energy
Intermittency

ABSTRACT

An understanding of household demand response (DR) is important in view of increasingly smart grids in which high shares of renewable supply are being promoted. In addition, an important development in the Nordic market relates to increasing thrust on household solar photo-voltaic (PV) panels. In view of the potential for interaction between dynamic pricing-driven and PV generation-driven load changes, an analysis of the combined effects in relation to the system profile is important, not least because this can affect the nature of benefits to households and to the grid. Using a unique and detailed dataset on household electricity consumption, in combination with simulated solar panel micro-generation data, these aspects are explored here using a demand framework drawn from the previous literature. Our findings indicate that even with low price responsiveness, household response to dynamic pricing can lead to load changes with sizeable benefits. In addition, the introduction of PV panels appear to be beneficial to the electric grid, largely due to the time pattern of winter PV generation. Overall, our findings provide tentative support to the hypothesis that dynamic pricing, by incentivizing households to provide demand response at appropriate times, can aid in integration of renewables.

1. Introduction

Electricity markets are facing challenging and remarkable changes whose main drivers relate to the intermittency in renewable generation and technical development in smart grids. Intermittency-related questions are at the forefront of research in energy economics (e.g., Gowrisankaran et al., 2016; Hirth, 2013, 2016; Hirth et al., 2015; Huuki and Karhinen, 2017). In the existing literature (e.g., Borenstein, 2012; Milligan et al., 2011) the integration costs of renewable resources (RES) are divided into three categories relating to uncertainty, locational specificity and variability. These costs will need to be taken into account in defining new models for pricing and regulation, and our analysis explores one important way of achieving that, household demand response (DR). Some of these cost-related aspects are often missing from policy discussions and ignoring them could lead to policy decisions imposing needlessly large costs.

Wolak (2017) identifies four major market design features that need to be considered in scaling-up intermittent renewable generation capacity, two of which (the second and the fourth) are directly relevant for this study. The first relates to finding efficient mechanisms for ensuring long-term resource adequacy. Current consensus in the literature suggests two approaches: capacity markets or energy-only markets, the former created by having electric utilities bid their willingness to keep idle capacity to be called on when needed while the latter are created through trusting that load can be adjusted based on renewable supply and demand response. Energy-only markets, in fact, turn the electricity production process up-side down; instead of dispatching generators based on demand, as is common, demand is 'dispatched' based on supply. This aspect relates closely to our research question in this paper.

The second feature, active involvement of final demand, particularly households in the wholesale and retail markets is the focus of our analysis. Policy makers in particular have argued that there is a large scope for involving households as active participants in the electricity market via price-driven demand flexibility (see e.g. Energimarknadsinspektionen,

* Corresponding author at: Department of Forest Economics, Swedish University of Agricultural Sciences (SLU), Umeå, Sweden.
E-mail addresses: chandra.kiran@slu.se (C.K.B. Krishnamurthy), mattias.vesterberg@umu.se (M. Vesterberg), herman.book@fmi.fi (H. Böök), anders.lindfors@fmi.fi (A.V. Lindfors), rauli.svento@oulu.fi (R. Svento).

https://doi.org/10.1016/j.enpol.2018.08.024
Received 5 March 2018; Received in revised form 30 June 2018; Accepted 10 August 2018

2016), motivating our focus on households. Per this feature, efficient pricing entails the default price for marginal consumption for all consumers be one that encompasses the system-wide cost (commonly the hourly spot price), including the costs of managing intermittent generation. In any case, this form of pricing is still a long-run target since the share of these types of voluntary contracts among households is increasing very slowly (e.g., in Finland about 5% of customers have real-time price based contracts, while for Sweden, it is lower still—less than 1%). The other side of this demand response coin relates to household-level small scale renewable production through solar panels. This aspect has not, to our knowledge, been explored for the Nordic setting. Its importance will be subsequently illustrated but the key linkage is the connection between the pattern of microgeneration and system characteristics, aspects which have been shown to be of importance for a specific setting (Gowrisankaran et al., 2016) when analysing the systemic implications of distributed generation. These aspects, we illustrate, will also be of substantial importance to understand for the Swedish context.

Our objective here is to evaluate two distinct, and inter-related, aspects concerning price-based household DR: the extent to, and the manner in which elastic households are able to respond to real-time pricing (RTP); and the interaction between this response and (household) micro-generation via roof top solar photo-voltaic panels ("micro-generation"). Household RTP and solar PV penetration are both major policy goals for Sweden (Lindahl, 2014) and both relate to penetration of intermittent sources, albeit via very different avenues. These issues are explored here by combining a rich household consumption data set with accurately simulated solar generation data, generating a unique data set. Our consumption dataset consist of hourly end-use specific observations for a random sample of Swedish households while our solar generation data are derived specifically for this analysis based upon the HARMONIE Numerical Weather Prediction (NWP) model (Bengtsson et al., 2017). To our knowledge, RTP and micro-generation have not been analysed previously at the household level.

It will be useful to very briefly recall a few features of RTP prominent in the received literature before we detail our objectives. The long-run—in which capacity and generation technology are allowed to change– benefits of RTP arise from both demand and supply adjustments, with peak(er) power capacity being reduced following adjustments on the demand side. Overall, prices fall, consumers experience welfare increases and the system experiences increased efficiency. When RTP is optional it is in fact the short-run—with fixed capacity and technology–effects of RTP which affect the realization of the envisaged long-run benefits. We focus on the short-run, and in our counter-factual scenario assume mandatory RTP for the sample households, and note that there has thus far been limited attention paid to short-run analysis of RTP for the Nordic setting (we are unaware of any studies using household data).[1] In any case, the only short-run analysis using household data we are aware of, Vesterberg and Krishnamurthy (2016), was focused upon evaluating the potential for RTP. Prior short-run household-data-based analyses of RTP, largely counterfactual (e.g., Borenstein, 2013a; Horowitz and Lave, 2014) but occasionally empirical (Allcott, 2011), have been focused on settings with regulated utilities, infrequently revised power rates, and very different generation and demand patterns from the Nordic setting. Consequently, aspects of micro-generation considered here differ from those in the existing literature.

[1] Prior long-run analyses of RTP in the Nordic setting (Kopsangas-Savolainen and Svento, 2012) indicate the usual sources of efficiency gains. A more recent study (Huuki and Karhinen, 2017) considers explicitly the role of RTP (of residential electric water boilers only) in helping to integrate wind in the Nordic grid, and finds, in simulations with a representative consumer, that in the long run the integration costs of wind can be substantially reduced if consumption based demand response is complemented with supply side hydropower optimization.

This paper explores two thus far unexplored aspects related to demand response for the Nordic setting. The first question is regarding the ideal household load profile under RTP, for a highly competitive retail market setting in the short-run. When costs of different sources of power vary sizably, with peak(er) power being more expensive, the ideal load profile is, ostensibly, one with small peaks, with the theoretical ideal being a rather flat load profile, as implicitly assumed in many previous studies. The extent to which this idealized load profile can be realized, in turn, depends upon two factors: (i) the level and time-pattern of price elasticity; and (ii) levels of price differentials across the day, in particular between peak and off-peak hours. To the extent that price differentials across hours are pronounced, the effect of a given pattern of elasticity is amplified. However, we illustrate that, at present, intra-day variability in the spot price (on average) is rather low, limiting the degree to which consumers can be incentivised to shift. Our analysis extends the prior work of Vesterberg and Krishnamurthy (2016) – in which the potential for, and benefits of, load shifts were examined – to settings where price responsiveness patterns represent consumers' willingness to do change load (encompassing cases of both energy conservation and load shifts). It also relates to prior examination of short-run effects of RTP upon consumer welfare (Borenstein, 2013a; Borenstein and Holland, 2005; Horowitz and Lave, 2014), particularly since the framework of analysis used here has many similarities with those used in this literature.

The second question relates to household load changes resulting from micro-generation, and the effects this has upon demand when households are assumed to be on an RTP contract. The two factors, RTP and micro-generation, represent the confluence of technological developments and energy policy, and present both an opportunity as well as a challenge for electricity markets. A key aspect determining the overall effect of these two factors is the relative timing of demand and supply. In any case, the interplay between the timing of the household (and system) peak, timing of micro-generation, and (observed and conjectured) demand response is explored with the demand framework used here, by examining alternative patterns appropriate to the Swedish context. We note that our analysis is concerned with the sample households' behavior in the short-run, taking the spot market as exogenous. While explicitly accounting for the supply side is a topic for future work, we discuss the linkages to systemic questions, including the evolution of the spot price with substantial penetration of RTP contract share and intermittent generation, in Section 5.1.

In summary, while investigations regarding integration of intermittency is an active area of research, studies connecting household demand behavior to systemic features of a future grid are scarce. Our contribution here lies in making precisely this connection. Thus, our study connects the literature evaluating the short-run benefits of RTP to that speaking to the systemic challenges of intermittent generation integration.

The plan of the paper is as follows: Section 2 summarizes different data-sets used for the analysis, Section 3 lays out the demand framework used for our simulations, along with detailing the various scenarios considered; Section 4 discusses the results of our policy simulations and Section 5 concludes with a discussion of the implications for policy and suggestions for further research.[2]

2. Data

Two distinct datasets will be used for our analysis: one pertaining to very detailed household electricity consumption, and another providing very detailed and local estimates of solar PV generation. We begin with a brief introduction to the major features of the data sets used, noting

[2] Figures and tables for results not provided in the manuscript but discussed – often tangentially – in the text (e.g. in Section 4.1.3, where we discuss robustness to alternative prices and elasticities) are available upon request.