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An automated residential demand response pilot experiment, based on day-ahead dynamic pricing

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HIGHLIGHTS

- We present experimental demand response pilot results, based on dynamic prices.
- The pilot included smart whitegood appliances and smart domestic hot water buffers.
- The whitegood appliances, esp. the dishwashers, outperform the hot water buffer.
- The larger energy consumption of the buffer yields larger absolute savings.
- The large share of non-smart consumption is a financial risk for the end user.

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ABSTRACT

Dynamic pricing is a popular method to realize demand response. Automated response from smart appliances reduces the comfort impact for the users and hence reduces response fatigue concerns, while improving the price response. However, real-life experience with smart appliances is typically limited to heating and cooling appliances. The Linear pilot was a residential demand response pilot with 240 Belgian families using smart dishwashers, washing machines, tumble dryers and domestic hot water buffers in various experiments. Goal was to evaluate the performance of those smart appliances in real life circumstances for various applications of demand response. The results for the day-ahead dynamic pricing experiments, conducted from September 2013 till July 2014 at 58 families, are presented. These demonstrate a significant shift of the flexible share of the electricity consumption to the lower price periods. The dishwashers outperform the other appliances. The domestic hot water buffer shows the lowest performance in terms of relative cost savings, but its much larger energy consumption translates to larger absolute savings. As the flexible share of the total consumption remains small, the non-smart share represents a financial risk for the consumer. The smart appliances were well received by the users and no response fatigue was observed. However, there was a high variation in the group of pilot participants, both in terms of energy consumption as in terms of flexibility offered.

1. Introduction

Demand response (DR) is increasingly deployed in the European industry to extend the traditional production-based balancing and congestion management reserves of Balancing Responsible Parties (BRP), Distribution System Operators (DSO) and Transmission System Operators (TSO). The large DR potential in the European residential sector, on the other hand, remains hitherto unused, as other criteria than for the industry apply; comfort protection is a basic requirement to enable sustained participation of families in DR schemes, the sources of flexibility are small in power and energy, but their numbers are large, etc. As such, the technology required to unlock the residential potential is fundamentally different from the DR technology used in the industry.

The Linear residential demand response pilot [1,2] aspired to bridge this gap and for this purpose, tested various residential DR technologies and control schemes in practice. One of the schemes developed and tested in Linear aims at realizing automated residential DR based on day-ahead dynamic pricing (DP), i.e., to have 'smart' appliances autonomously react to variable prices, within the comfort settings of the users. The technical goal

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of the Linear tariff structure is to help compensate for day-ahead predicted variations in wind and solar energy, while at the same time ameliorate distribution grid congestion.

After situating the Linear residential automated DR/DP approach in the field of residential DR pilots (Section 2), we elaborate on the tariff structures (Section 3). Section 4 describes the Linear pilot setup, followed by the dynamic pricing control algorithm specification (Section 5). In Section 6 the measurement results from the Linear residential demand response pilot are presented and analyzed and Section 7 summarizes the feedback from the users.

2. Related work

Due to its technical simplicity, dynamic pricing (DP) is a popular method in attempts to influence the electrical energy consumption of residential end-users. The most straightforward application of dynamic tariffs is via manual demand response, i.e., to inform the end-user of the variable prices and to rely on that same user to manually shift electrical consumption from the expensive periods to the cheaper ones. However, a point of debate is the concern regarding the decreasing efficiency of such manual schemes due to 'response fatigue'; the end-user tires of continuously checking prices and the resulting comfort impact, resulting in decreased involvement or a switch to non-dynamic pricing schemes. The literature is indecisive on this topic [3–6]. An alternative dynamic pricing DR scheme that circumvents the response fatigue concern, is automated DR. Here, smart appliances respond to the prices, where the impact on the user's comfort is limited to the configuration of those smart appliances (see Section 4). As a complex tariff scheme was rolled out in the Linear pilot (see Section 3), concerns regarding response fatigue arose and it was decided to deploy both manual and automated DR for the dynamic pricing experiments, the latter of which is discussed here. The choice for automated demand response was further supported by the evidence that this improves the price response [7], up to 200% compared to manual response [8–10].

Many examples of simulations [11–15] and lab tests [16–19] can be found in the literature, proposing and evaluating a wide range of pricing schemes, smart appliances and control strategies. On the other hand, although a lot of residential demand response pilots have been conducted and even a fair number of commercial initiatives exist, especially in the U.S., the range of smart appliances covered by these initiatives is limited [7–10,20–26]. Most do not include smart appliances and are based on manual response solely, and those that do include smart appliances limit automated control to heating or cooling appliances, and – rarely – pool pumps. For the European commercial variable pricing schemes, e.g., Option tempo in France, PVPC in Spain or Vattenfall's Nordic power exchange coupled variable pricing in Sweden [27], no public data is available if smart appliances are used within these schemes, nor with what success.

Two noteworthy exceptions are the pilot results discussed in [28,29]. In [28], the results for a German pilot are discussed, in which smart washing machines and tumble dryers were tested by 41 participants, using a pricing scheme composed of hourly prices set day-ahead to one of three price levels. However, the performance results are based on user interviews and dairies, and not on measurements. Ref. [29] describes the results of a Dutch pilot, more specifically of 50 smart washing machines used by participants to a dynamic tariff scheme. The tariffs are based on day ahead energy market prices and on the local transformer load, which contains a strong photovoltaic production component. Note that the results presented in [29] do not separate the impact of manual behavioral changes from the impact of the automated demand response actions. In Sections 6 and 7, the results from [29] are discussed in light of our own findings.

This paper presents the Linear pilot measurement results on the performance of smart Domestic Hot Water (DHW) buffers, smart washing machines, smart dishwashers and smart tumble dryers during day-ahead dynamic pricing experiments. We fill the gap of empiric data on the performance of all types of smart whitegood appliances under dynamic pricing in real life conditions, and compare this performance to that of the more commonly used DHW buffer.

3. Time of use tariff structure

The day-ahead dynamic tariff scheme used within Linear, consisted of several components: energy, distribution, transmission, and levies. Various ways exist to construct dynamic pricing structures from these components [30,31]. The Linear project opted for a dynamic energy and distribution component, and a constant transmission and levies component. The following paragraphs summarize how the dynamic components were constructed. More elaborate descriptions of the methodology can be found in [13,32]. The constant transmission and levies components are based on the Belgian averages and amount 10 €/MW h and 70 €/MW h, respectively.

The dynamic energy component is based on the historic Belgian day-ahead wholesale market prices of 2011 [33]. These historic prices were corrected to reflect a future larger share of renewable generation, according to the 2020 scenario defined in [34]. The [34] data was combined with public data on the annual generation profiles of solar and wind plants [35,36], to calculate the hourly power deviation from the historic power generation due to the increased share of renewable generation. This was converted into an hourly financial correction on the historic wholesale prices, using the wholesale price sensitivity for increases in offer or demand, as presented in the market resiliency analysis in [37]. Result is the adjusted hourly wholesale price ($WP_{adjusted,p}$).

As the wholesale price only accounts for part of the energy component, a second correction is needed in order to attain revenue neutrality [38]. A rescaling factor (rfe) was applied to ensure that the same revenues are accrued using the dynamic prices or the previously flat energy tariff, if the averaged residential user[1] does not change his consumption pattern (SLP_p). Or:

$$\sum_{p=1}^{8760}\left[\left(SLP_p \cdot WP_{adjusted,p}\right) \cdot rfe\right] = Flat_{Energy} \tag{1}$$

with SLP_p the synthetic load profile during hour p (% of yearly consumption) [39], $WP_{adjusted,p}$ the adjusted wholesale price during hour p (€/MW h), rfe the rescaling factor for the energy component and $Flat_{Energy}$ the (old) flat energy tariff component (€/MW h). $Flat_{Energy}$ was set to 80 €/MW h.

The dynamic distribution component varies with the level of the electricity usage of residential users according to the following formula:

$$RTP_{Distr,p} = \frac{SLP_p}{\sum_{p=1}^{8760} SLP_p^2} \cdot Flat_{Distr} \tag{2}$$

with $RTP_{Distr,p}$ the dynamic distribution tariff component (€/MW h) and $Flat_{Distr}$ the average distribution tariff component over the year (70 €/MW h).

The hourly distribution price is determined based on the ratio between the hourly usage and its weighted average over the year. This results in a higher distribution tariff when the hourly electricity usage of residential users is above the weighted average.

[1] Based on the official Synthetic Load Profiles (SLP), used in the Belgian energy market [39].