HEAT PUMP OPTIMIZATION STRATEGIES FOR PARTICIPATION IN PRICE-CONTROLLED DEMAND RESPONSE IN THE LATVIAN ELECTRICITY MARKET

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Improved end-user engagement is considered to be a key factor in decarbonization efforts towards climate neutral energy systems. While first adopters are already actively seeking ways how to optimize their energy consumption, a true shift in consumer behaviour can only be achieved if the financial benefits are well established and presented.

The study aims at estimating the economic performance of end-user engagement in provision of demand response services using air-to-air heat pumps as the underlying technology. The results of the paper help evaluate in a real data setting whether the existing market framework provides sufficient incentives to facilitate end-user participation in the demand response service.

Keywords: Demand response, electricity price, electricity markets, heat pumps.

1. INTRODUCTION

Traditionally, the balance between demand and supply in a power system is maintained by adjusting centrally controlled supply to largely inelastic demand. The increase in intermittent and distributed generation [1] as well as a continuous increase in demand for electricity not only promotes volatility of electricity prices, but also creates new challenges for the power system

infrastructure. An aspect of this is illustrated by the case of South Queensland (Australia) where during the period of 2009–2014 the total installed capacity of solar panels increased from 187 MW to 4092 MW [2] and percentage of residential consumers with rooftop solar panels reached 25 %. Such a shift reduced electricity volumes consumed through a distribution system

but did not have considerable impact on the costs of the system, the volume-based distribution system tariffs increased by 112 % [3].

With the emerging preference for electric transportation and heating, the demand for electricity has even more tendency to cluster in high and low demand periods, which may result in peak load demands increasing faster than the total annual consumption and adding additional price pressures to the electricity and power system alike. On the other hand, technologies enabling demand response offer an opportunity to mitigate the volatility of energy consumption patterns, which could help the power system adjust to the emerging and in some cases already established market requirements. The consideration that improving system flexibility is a key factor in reducing the costs of integrating intermittent generation has also been reinforced by recent studies [4]–[6]. For this

reason, encouraging consumer engagement in demand response activities has become an increasingly important energy policy topic [4], [7]–[9]. While there might be a discussion on whether facilitation of consumer engagement in the electricity market is necessary, how to achieve that is a challenge with a less clear solution. The objective of this paper is to compare easy-to-use cost optimization scenarios for an air-to-air heat pump based heating system. The rest of the paper is organised as followed: Section 2 presents market background and legal framework for the Latvian electricity market. Section 3 is devoted to the examination of contributing factors and barriers for consumer participation in demand response. This review serves as the basis for the case study design, which is described in Section 4. In the last section of the paper, the results of the case study and conclusions are presented.

2. BACKGROUND AND LEGAL FRAMEWORK

The EU energy policy foresees increased importance and integration of demand response, facilitated by smart meter rollouts, supportive legal framework and active consumer education. The recital of Council Directive 2019/944/EU (2019) foresees that “[..]Consumers should have the possibility of participating in all forms of demand response. They should therefore have the possibility of benefiting from the full deployment of smart metering systems and, where such deployment has been negatively assessed, of choosing to have a smart metering system and a dynamic electricity price contract. This should allow them to adjust their consumption according to real-time price signals that reflect the value and cost of electricity or transportation in dif-

ferent time periods, while Member States should ensure the reasonable exposure of consumers to wholesale price risk. Consumers should be informed about benefits and potential price risks of dynamic electricity price contracts [...]”. In its turn, Article 11 stipulates that “Member States shall ensure that the national regulatory framework enables suppliers to offer dynamic electricity price contracts. Member States shall ensure that final customers who have a smart meter installed can request to conclude a dynamic electricity price contract with at least one supplier and with every supplier that has more than 200 000 final customers” [10]. According to CEER in 2018, 21 out of 27 Member States offered some type of variable price contracts and

only in 15 out of 27 Member States spot-price tied contracts were available to residential users [11].

Electricity market liberalization started in Latvia in 2007 when the option to freely choose an electricity supplier was offered to business consumers with high consumption. Furthermore, such an opportunity was offered to business consumers with medium consumption on 1 April 2012 and to all other business consumers on 1 November 2012. The market was opened to residential consumers on 1 January 2015. While the electricity suppliers in Latvia are required to offer a “universal product” to residential

consumers, the Latvian legal framework does not require electricity suppliers to offer dynamic electricity price contracts. According to the data published by the Public Utilities Commission of Latvia, 12.5 % (a three-fold increase from the end of 2017) of residential consumers and 42.8 % of business consumers (~30 % increase from the end of 2017) chose a dynamic pricing type of contract (Figs. 1 and 2) [12]. Currently, most of electricity suppliers provide some type of dynamic price contracts (either time-of-use [13] or spot-price tied [14]) to both business and residential consumers.

Fig. 1. Contract type structures for residential consumers in Latvia, 2017–2020. Data source: [11].

Fig. 2. Contract type structures for business consumers in Latvia, 2017–2020. Data source: [11].

To look at overall consumption pattern trends in Latvia, the year 2020 is excluded due to a considerable, but not easily measurable impact of pandemic. By comparing day-ahead market volumes for 2017 and 2019, it can be observed that while the overall volumes increased the volatility of

the volumes bought decreased (see Table 1) [15]. Despite a positive trend, more research should be conducted to explore the drivers behind it. The data also show high variations between peak and off-peak demand and a potential for an implicit demand response to facilitate it.

Table 1. Comparative Descriptive Statistics for Energy Volumes Sold on NordPool Day-Ahead Market in 2017 and 2019 [14]

Parameter	2017	2019	Deviation
Sum	7.2 TWh	7.3 TWh	+0.7 %
Mean	828 MWh	834 MWh	+0.7 %
Standard deviation	177 MWh	167 MWh	-5.9 %
Range	828 MWh	742 MWh	-10.4 %
Minimum volume	444 MWh	479 MWh	+7.9 %
Maximum volume	1 272 MWh	1 222 MWh	-4.0 %

3. BARRIERS FOR CONSUMER ENGAGEMENT IN DEMAND RESPONSE

Residential consumer engagement (or lack of it) can be divided into stages, each characterised with different preconditions. EPRI (2012) proposes the following

three-step structure: participation (being enrolled in demand response), performance (responding in the desired way) and persistence of effects over time (Fig. 3) [4], [16].

Fig. 3. Three stages of consumer engagement in demand response. Adapted from [3].

Understanding the barriers and drivers of long-term active participation in demand response can allow policy makers and market actors to identify and foster consumer engagement in a more cost-effective way and assess the potential for demand side response participation in a more precise manner.

Parrish et al. (2020) identified the following types of motivators: financial, environmental and social. Based on multiple

studies, the financial incentives are the most important [4], [17]–[23]. Financial incentives include reduced monthly bill, rewards for specific consumption patterns, free or reduced cost technology [4]. Environmental motivators are less studied and seem to play a less important role as participation in demand response does not necessarily decrease the overall consumption [4], [24]. Social motivators include increased perceived control over energy consumption

[17], [24], finding the experience novel and entertaining [17] or taking pride in being socially responsible or supportive to the energy system [4], [25], [26].

These benefits or motivators are usually weighed against effort, time, conve-

nience, and comfort [4], [27]–[29]. Based on the systemic review by [4], real financial benefits serve as a necessary precondition for meaningful participation in implicit demand response activities.

4. CASE STUDY DESIGN

Heating, ventilation, and air conditioning (HVAC) systems have a tendency in developed countries to become more prevalent over time [30]. For example, in Latvia, 6 % of residential buildings had electricity-based heating and ~2 % of residential buildings had air conditioning in 2015 [31]. It should be noted that HVAC tends to be one of the most energy intensive residential types of electric appliances. The exact estimation for the proportion of electricity consumption for which HVAC is responsible is hard to come by as these estimates will differ on climate, building and other appliances. On average, it is considered that heating is responsible for up to 50 % of the monthly electricity consumption during a peak demand period [32].

By reviewing the existing literature on HVAC control system testing and designing, it can be observed that while there are

different energy efficiency objectives or particular challenges of multi-building or multi-zonal systems, a general approach to introducing deterministically controlled HVAC system is fairly simple and requires data collection, algorithm and load controller device [32]–[35]. The objective of this study is to evaluate in a real data setting the most appropriate algorithm for implementing automatic and cost-efficient HVAC system management that relays on publicly available data. To achieve the objective for the set period of time (in December 2020 and January 2021), four HVAC systems were monitored. Afterwards, alternative optimization approaches were tested. The best performing algorithm is further intended to be used for HVAC management. Table 2 and 3 present the case study environment and describe the data used, respectively.

Table 2. Description of the Case Study Environment

HVAC systems used	One Toshiba Premium air-air type of heat pumps (RAS-25PAVPG-ND), with heating capacity of 0.7–6.70 kW and three Toshiba Optimum (RAS-25PKVSG-ND) heat pumps 1.00–6.50 kW were chosen
Area	Two isolated rooms of 26 m ² (set indoor temperature of 17 °C) and 23 m ² (set indoor temperature of 17 °C) and a large hall of 70 m ² (set indoor temperature of 19° C with some HVAC unrelated temperature fluctuations due to ventilation or use of other devices)
Period	24 days, December 2020–January 2021

Table 3. Description of the Data Used in the Case Study

Outside temperature	Factual hourly data from metrological data from the Latvian Environment, Geology and Meteorology Centre (°C) [35]
Day-ahead prices	Factual hourly data from NordPool exchange (EUR/MWh) [15]
Heat pump load	Measured every minute (MW)

In the context of this study, the following assumptions (simplifications) were made – firstly, the load was only shifted and there was no reduction of total consumption (rebound effect expected to be 100 %). The consumption from the hour when the system is turned off is shifted to the next two hours. The determination of the exact nature of the rebound effects in different condi-

tions is outside the scope of this study and is left for further research. This assumption prescribes that switching off may not occur more often than once every two hours (the condition is also observed during the date change).

The following optimization scenarios were devised (Table 4).

Table 4. Optimization Scenarios Used in the Case Study

Scenario	Conditions	Objective
Selecting <u>two hours</u> in every given day, when the HVAC is switched off, is based on the following criteria:		
2-1	The lowest temperature	Representation of the highest expected consumption [36]
2-2	The highest day-ahead price	Representation of the highest cost per MWh
2-3	The highest projected cost savings from load shifting	Representation of the highest total gains from shifted consumption
Selecting <u>three hours</u> in every given day, when the HVAC is switched off, is based on the following criteria:		
3-1	The lowest temperature	Representation of the highest expected consumption
3-2	The highest day-ahead price	Representation of the highest cost per MWh
3-3	The highest projected cost savings from load shifting	Representation of the highest total gains from shifted consumption

The highest projected costs savings (C_{H0}) from load shifting were calculated as follows:

$$C_{H0} = E_{H0} \times P_{H0} - E_{H0} \times \frac{P_{H1} + P_{H2}}{2}, \quad (1)$$

where

C_{H0} – expected costs savings from load shifting (EUR);

E_{H0} – energy volume shifted from hour H_0 to hour H_1 and H_2 (MWh);

P_{H0} , P_{H1} , P_{H2} – day-ahead price for hour H_0 , hour H_1 , hour H_2 , respectively (EUR/MWh).

The expected energy volume E_{H0} shift was calculated based on the empirically obtained relationship for a particular HVAC system:

$$E_{H0} = 0.001288 - 0.00015 T_{H0}, \quad (2)$$

where

T_{H0} – expected temperature at hour H_0 (°C).

The empirical equation (Fig. 4) was obtained by applying linear regression to the empirical consumption and factual temperature data from the case study.

Fig. 4. Hourly HVAC consumption and temperature data during the study. Temperature data source [34].

The optimization algorithm selects the best fit based on the conditions described above. In case the best fit violates the con-

dition that HVAC may only be switched off no more often than once every three hours, the next best fit is selected.

5. RESULTS AND CONCLUSIONS

During the observation period the following data were collected in regard to

outdoor temperature, day-ahead price and actual HVAC consumption (Table 5).

Table 5. Descriptive Statistics of Temperature, Electricity Price and HVAC Consumption during the Case Study. Data sources – temperature [34], electricity prices [14]

Parameter	Temperature (°C)	Day-ahead price (EUR/MWh)	HVAC actual consumption (kWh)
Mean	0.1	43.89	1.26
Range	9.9	197.21	1.77
Minimum	-4.6	2.75	0.58
Maximum	5.3	199.96	2.36

The scenarios previously described provide the following outcomes (Table 6).

Table 6. Optimization Scenario Output Comparison

Scenario	# of hours selected per day	Total consumption (kWh)	Total cons. shifted (kWh)	Percentage of cons. shifted	Total cost of electricity (EUR)	Cost difference from base scenario
Base	0h	748.42	-	-	33.58	-
2-1	2h	748.42	70.94	9.5 %	33.58	0.01 %
2-2	2h	748.42	65.37	8.7 %	32.94	-1.90 %
2-3	2h	748.42	67.42	9.0 %	32.18	-4.18 %
3-1	3h	748.42	104.64	14.0 %	33.54	-0.13 %
3-2	3h	748.42	97.36	13.0 %	32.68	-2.69 %
3-3	3h	748.42	99.43	13.3 %	31.97	-4.81 %

The relative performance of the scenarios was similar in both two-hour and three-hour scenario groups. The highest load shift was observed in a scenario where the load was shifted away from the coldest hours (in a two-hour scenario – 9.5 % of total load was selected, while in a three-hour scenario 14.0 % of load was shifted). However, neither scenario 2-1 nor 3-1 resulted in noticeably different total costs regarding the base case scenario. This might be related to the following: the coldest hours are typically during the night when the electricity price dynamic is less pronounced. Scenarios 2-2 and 3-2 in both two-hour and three-hour groups demonstrated similar relative performance in their scenario groups; however, the best performing scenario was 2-3 and 3-3 that considered both the expected

difference in price and the expected loads. The improved economic performance over scenario 2-2 and 2-3 is considerably higher than the increased load shift. This indicates that a sub-optimal choice is considering day-ahead prices and not taking into account the expected consumption level.

Overall, results of the case study suggest that the immediate benefits from load-shifting are modest. Taking this into account, if the energy policy maker considers and identifies that active engagement of residential consumers in implicit demand response activities is pivotal for better integration of intermittent and distributed generation as well as power system optimization, additional incentives reflecting overall system benefits from more moderate peak and off-peak loads might be considered.

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