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Reduction of Price Volatility using Thermostatically Controlled Loads in Local Electricity Markets

Shantanu Chakraborty, Remco Verzijlbergh, Zofia Lukszo
Faculty of Technology, Policy, and Management
Delft University of Technology
Delft, Netherlands 2628BX
Email: S.T.Chakraborty@tudelft.nl

***Abstract*—Price volatility in electricity markets could significantly increase as a result of the increase in demand due to the electrification of heating and transport and intermittent power generation from large scale integration of renewable energy sources. In some parts of the grid, price volatility may be even more extreme due to congestion. Energy storage and price responsive demand provide a potential source of flexibility to reduce excessive variations in price. In this paper, we investigate the potential of one such type of price responsive demand, namely thermostatically controlled loads, to mitigate against this adverse economic effect through a coordination mechanism that gives explicit constraints on the local electricity price. In a simulation based study that focuses on an energy community situated in a congested part of the distribution grid, we investigate to what extent thermostatically controlled loads can provide load reduction in order to cap prices at a specified limit. Results show that congestion and the resulting price spikes can effectively be mitigated by exploiting the thermal inertia of the households.**

I. INTRODUCTION

Energy communities comprise of a group of consumers that organize themselves to achieve objectives such as energy cost reduction and are characterized by the presence of distributed energy resources. To satisfy its energy demand, the community interacts with the main grid, thereby exposing itself to price volatility in the wholesale market. Given the variable nature of renewable energy and the uncertainty in power consumption, prices can vary significantly [1] in the wholesale market. Price volatility can be further exacerbated due to spikes in power consumption or line congestions [2]. This phenomenon has been experienced worldwide in places such as Denmark, Germany [3], and the United States [4].

To curb the increase of price volatility, supply-side flexibility options have been investigated [3], [5]. However, their impact is limited due to uncoordinated flexible resources or high power consumption during peak periods [6] resulting in increased grid congestions. In contrast, this paper focuses on demand-side flexibility which compliments the variable generation of renewables and is better suited for reducing price volatility. Demand-side flexibility can be availed from electricity storage, flexible consumption through variable pricing and demand response, and through community-based flexibility markets with aggregator participation. Electric storage provides the opportunity to leverage inter-temporal flexibility thereby reducing consumer exposure to steep prices. Under variable pricing schemes and demand response, the optimal management of flexible loads such as electric vehicles [7], refrigerators [8], and aggregated building loads [9] can contribute towards reduction of electricity price. Finally, from a market perspective, community-based flexibility markets with aggregator participation [10] enables increased integration of renewables while accounting for price volatility.

However, previous research does not take into account the possibility of constraining the price volatility to consumer willingness to pay for electricity. To address this research gap, this paper explores a mechanism that enables communities to set an upper bound on price spikes in the local electricity market. The proposed mechanism quantifies the amount of flexibility that the aggregator needs to generate through flexible generation or load reduction for constraining price. In this research, we refer to the taking of actions in the current instance to constrain price volatility as *hedging*. While hedging in electricity markets has traditionally been performed through forward contracts, present day markets with increased volatility need more dynamic mechanisms. To this end, [11] investigates the possibility for hedging in day-ahead markets using flexible resources and additionally performs a comparative analysis between forward contracts, call options and incentivizing consumers for flexibility provision. Their work, however, does not take into account price limits or aggregator involvement in the hedging mechanism.

Hedging, in the context of our research is achieved by constraining price by providing demand-side flexibility. This approach is grounded on duality theory and through it in the day-ahead market we can ensure that consumers do not pay a price which is higher than their maximum willingness to pay for electricity. The main feature of the formulation is that by applying duality theory, explicit constraints can be placed on electricity prices, which are not known a priori. Due to the addition of the price constraints in the dual formulation, a new variable corresponding to the amount of demand-side flexibility is introduced in the primal problem. As our work leverages physical components for flexibility provision to hedge against price spikes, we introduce the concept of physical hedging as opposed to purely financial hedging.

Initial results from the application of the proposed hedging mechanism is presented in [12], [13], [14]. In these works, we have established the mathematical formulation of the physical hedging and explored its effectiveness under uncertainty and the impact of grid constraints. While our previous work has considered the source of the demand-side flexibility to be an electric storage system, in this work, we have considered the source of the flexibility to be thermostatically controlled loads such as heat pumps. Previous research on thermal loads have been focused on load planning for demand response [15] and energy arbitrage [16] and have not considered their potential to contribute to constraining of prices. Thus, our work contributes to the scientific literature by investigating the potential of thermostatically controlled loads (TCL) to reduce price volatility in electricity markets by constraining the price to an upper limit, and quantifying the load reduction required. Additionally, we provide a coordination framework for facilitating the physical hedging using thermal loads. It is expected that our formulation under the assumption of dynamic pricing and electric heating can safeguard consumers against rapid price fluctuations.

The structure of this paper is as follows: first we present the formulation for estimating the amount of flexibility through load reduction required in the operation of the thermal load. We then present the information flow between actors required for facilitating the coordination. Next, the data for the simulation, its setup is presented followed by a discussion of the results. Finally, we draw conclusions from our results and provide recommendations for future research.

II. PROPOSED APPROACH TO USE THERMOSTATICALLY CONTROLLED LOADS FOR REDUCING PRICE VOLATILITY

This Section focuses on the ability of TCLs to limit price spikes to desired bounds in electricity markets. The fundamental idea of the approach is to apply an explicit constraint on price. In an economic dispatch formulation, price is the dual variable associated with load balancing, representing the cost of supplying an additional unit of power. In this formulation, if we assume Slater's conditions to hold, and because the primal problem is convex, strong duality holds between the primal and dual problems. Applying a constraint on price in the dual formulation will result in the introduction of a new variable in the load balancing equation in the primal problem. This new variable corresponds to the required flexibility for constraining price to the desired limit. For example, if we want to constrain price to $\overline{\lambda^*}$, and if the market price is $a : a > \overline{\lambda^*}$, then to constrain the price using our formulation, we will need to quantify and facilitate the required flexibility P_F.

In this paper, we provide a generalized formulation of our approach through Equation (1). For a detailed derivation of our formulation, we draw the readers attention to [12], [13].

$$\min_{P_{G_i},P_{F_i}} \sum_{t\in T}\sum_{i\in\mathcal{N}} \left(a_i[t]P_{G_i}[t] + \overline{\lambda^*}_i[t]P_{F_i}[t]\right) \tag{1}$$

subject to:

$$P_{G_i}[t] - P_{L_i}[t] + P_{F_i}[t] = \sum_{j\in\Omega_i} \frac{\theta_i[t]-\theta_j[t]}{X_{ij}} \quad \forall i\in\mathcal{N}, \forall t\in T \tag{1a}$$

$$-\overline{P_{ij}} \le \frac{\theta_i[t]-\theta_j[t]}{X_{ij}} \le \overline{P_{ij}} \quad \forall (i,j)\in\Omega_{ij}, \forall t\in T \tag{1b}$$

$$\theta_{slack} = 0 \tag{1c}$$

$$0 \le P_{G_i}[t] \le \overline{P_{G_i}} \quad \forall i\in\mathcal{N}, \forall t\in\mathcal{T} \tag{1d}$$

$$P_{F_i}[t] \ge 0 \quad \forall i\in\mathcal{N}, \forall t\in\mathcal{T} \tag{1e}$$

Equation (1) represents the economic dispatch problem for a medium voltage (MV) distribution grid which has been modified to account for our proposed price constraining formulation, with $\overline{\lambda_i^*}$ representing the price limit. Load balance at all nodes in the network, denoted by $\mathcal{N}$, is given by Equation (1a). At a subset of these nodes, flexible resources can be availed for constraining price to a community specified upper price limit. By solving Equation (1), we determine a time-varying signal $P_{F_i}[t]$, required for constraining price.

In this work, we focus on the potential of TCLs to satisfy the flexibility request signals $P_F[t]$ at a given node. The TCL considered is a heat pump. Through a three-step procedure, we determine the change in TCL operational profile to provide the required flexibility. First, we determine the operational profile of the heat pump assuming a constant price in the electricity market. Under this scheme, the heat pump operates only to compensate for the heat loss to the ambient surroundings, and restricts the room temperature from decreasing below a specified room temperature limit. This determines the reference heat load profile. The second step, comprises of estimating the required flexibility for constraining the price to the community specified limit of $\overline{\lambda^*}$. Finally, in the third step, we compute the new operational profile of the heat pump for satisfying the flexibility requests considering time-varying electricity prices. The formulation for computing the reference power consumption profile of the heat pump for a given household is based on [16] and expressed as follows:

$$\underset{P_{hvac}}{\text{minimize}} \sum_{t=1}^{T} P_{hvac}[t] \tag{2}$$

subject to:

$$T_{r_h}[t+1] = T_{r_h}[t] + \frac{1}{C_{p,r_h}}\Big\{(UA)_{f,r_h}(T_{f_h}[t]-T_{r_h}[t]) - (UA)_{r,a_h}(T_{r_h}[t]-T_a[t])\Big\} \quad \forall t\in\mathcal{T} \tag{2a}$$

$$T_{f_h}[t+1] = T_{f_h}[t] + \frac{1}{C_{p,f_h}}\Big\{(UA)_{w,f}(T_{w_h}[t]-T_{f_h}[t]) - (UA)_{f,r_h}(T_{f_h}[t]-T_{r_h}[t])\Big\} \quad \forall t\in\mathcal{T} \tag{2b}$$

$$T_{w_h}[t+1] = T_{w_h}[t] + \frac{1}{C_{p,w}}\Big\{\eta P_{hvac_h}[t] - (UA)_{w,f}(T_{w_h}[t]-T_{f_h}[t])\Big\} \quad \forall t\in\mathcal{T} \tag{2c}$$

$$\underline{P_{hvac_h}} \le P_{hvac_h}[t] \le \overline{P_{hvac_h}} \quad \forall t\in\mathcal{T} \tag{2d}$$

$$\underline{\Delta P_{hvac_h}} \le P_{hvac_h}[t+1] - P_{hvac_h}[t] \le \overline{\Delta P_{hvac_h}} \quad \forall t\in\mathcal{T} \tag{2e}$$

$$\underline{T_{r_h}} \leq T_{r_h}[t] \leq \overline{T_{r_h}} \quad \forall t \in \mathcal{T} \tag{2f}$$

The objective of Equation (2) is to reduce the amount of power consumed by the heat pump power for a given household and it is denoted by the variable P_{hvac_h} where h indicates the household. Equations (2a) - (2c) denote the temperature dynamics for the room, floor, and water in the tank heated by the heat pump. The temperature dynamics inside the household are modeled through conductive heat transfer: they depend linearly on the temperature differences and conductance between the components. In Equation (2a) the thermal capacitance of the room, and heat conductivity from the floor to the room, and room to surroundings are given by variables C_{p,r_h}, $(UA)_{f,r_h}$ and $(UA)_{r,a_h}$ respectively. Equation (2b) represents the temperature dynamics for the floor temperature. Variables C_{p,f_h} and $(UA)_{w,f}$ represent the thermal capacitance of the floor and the heat conductivity from the water tank to the floor. The temperature balance for the water tank is expressed in Equation (2c). Capacitance of the heat pump and its coefficient of performance (CoP) is given by $C_{p,w}$ and η respectively. The operational bounds of the heat pump is expressed using Equation (2d). Ramp constraints for the heat pump operation and bounds on the temperature values of the room are expressed through Equations (2e) - (2f) respectively. As there are multiple households in a community, we consider the temperature preferences of each consumer as well as the varying physical characteristics of their households. The aggregation of the heat pump power consumption $P_{agg}[t]$ across consumers for each time step is then computed.

In the second step, we determine the amount of flexibility through load reduction required for constraining price which is achieved by executing Equation (1). For the community, the power demand in Equation (1) is divided into aggregated baseload (without thermal load) and thermal load values. Hence, the load value $P_{L_i}[t]$ in Equation (1a) is now represented as follows:

$$P_{L_i}[t] = \underbrace{\overline{P_{L_i}[t]}}_{\text{agg. baseload}} + \underbrace{P_{agg_i}[t]}_{\text{agg. thermal load}} \quad \forall t \in \mathcal{T} \tag{3}$$

The quantified flexibility P_F is now satisfied by load reduction provided from the heat pumps. For doing so, the operational schedule for the heat pumps needs to be re-computed using Equation (4). The goal of Equation (4) is to satisfy load at lowest possible price in addition to facilitating the requested flexibility, which is achieved through the differences in the heat pump operation. Terms used in the objective function comprise of the time-varying price of electricity c, the new heat pump operating profile for each household P_{new_h}, and indices h and t correspond to the set of households and simulation period, H and $\mathcal{T}$ respectively.

$$\underset{P_{new}}{\text{minimize}} \sum_{t=1}^{T} c[t] \sum_{h=1}^{H} P_{new_h}[t] \tag{4}$$

subject to:

$$\text{Equation (2a) -- Equation (2f)} \tag{4a}$$

$$P_{F_i}[t] = P_{agg_i}[t] - \sum_{h=1}^{H} P_{new_h}[t] \text{ if } (P_F[t] > 0) \forall t \in \mathcal{T} \tag{4b}$$

Equation (4a) states that the constraints for individual houses are the same as specified in Equation (2). With Equation (4b), we enforce the constraint for satisfying the load reduction requests across the community. Hence when $P_F[t] > 0$, then the difference between the previous aggregated and the new aggregated heating profile for the community must satisfy $P_F[t]$ in order to constrain price. This enables heat pumps to hedge against spikes in the electricity price. Thus, a benefit of our proposed approach is that it extends market based approaches to congestion management by enabling direct load control by a market entity who ensures a specified maximum price limit. Finally, it should be noted that the present work aims at constraining price at an hourly interval only. Through the application of constraints to dual variables at an aggregated level, it is possible to constrain price at the daily and monthly levels and will be investigated in subsequent works.

III. INFORMATION FLOW BETWEEN ACTORS

This Section highlights the information flow between actors for facilitating the proposed coordination mechanism. Actors involved in the coordination include the Distribution System Operator (DSO), an aggregator and the energy community who are connected to the MV network. The proposed coordination mechanism is illustrated through Figure 1.

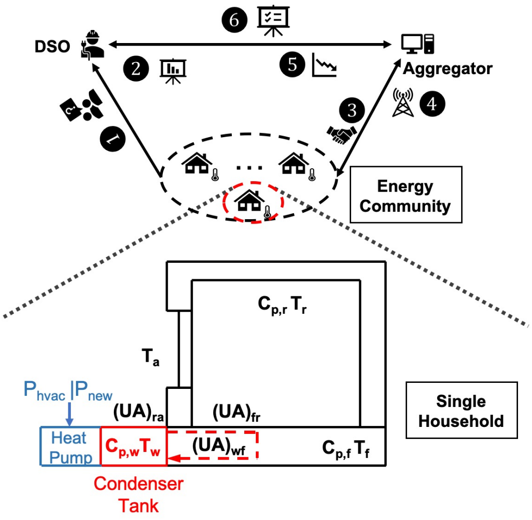

Fig. 1: Information Flow

This coordination mechanism is initiated when an energy community, to protect themselves from price spikes, communicate their desired upper price limit to the DSO (1). The DSO participates in this mechanism as a regulated market entity with information about market price and grid structure, enabling them to execute Equation (1) and quantify the flexibility required to constrain price. This information is then communicated to the aggregator (2), who seeking a business opportunity can enter into a contract with the community (3), and subsequently operate their heat pumps (4) to satisfy the requested flexibility. After computing the modified TCL schedule using Equation (4), the aggregator informs the DSO about the load reduction (5). Finally, the DSO coordinates with the aggregator for clearing the local market (6).

Thus, through the proposed coordination mechanism, the energy community can physically hedge against the price spikes using TCLs, and remunerate the aggregator for its services. Finally, it should be noted that while our focus in the present work has been at the DSO network, the formulation can readily be extended to higher voltage levels such as the Transmission System Operator (TSO) network.

IV. SIMULATION AND RESULTS

In this Section, we first provide information about the data used for the simulation, the simulation tool used, and then discuss the results generated. For simulation of the heat pump, we use data provided in [16]. As [16] focuses on a single dwelling, to generate heat pump profiles for the community we randomize parameters over a normal distribution for parameters such as $(UA)_{f,r}$, $(UA)_{r,a}$, $C_{p,r}$ and $C_{p,f}$. The base case value for these parameters are $(UA)_{f,r}$ =624$kJ/(^\circ Ch)$, $(UA)_{r,a}$ =28 $kJ/(^\circ Ch)$, $C_{p,r}$ =810$kJ/^\circ C$ and $C_{p,f}$ =3315 $kJ/^\circ C$. Finally, the values of $(UA)_{w,f}$ =28$kJ/(^\circ Ch)$, $C_{p,w}$ =836$kJ/^\circ C$ and heat pump CoP η =3 are assumed constant for the community. For the purpose of our simulation, we assume the community to comprise of H =14 households. Each community member has their own temperature preferences limits which are within the range from 18°C to 26°C. Additionally, the initial temperature set points of the room, floor and water in the heat pump differs per household which are sampled from a normal distribution.

Each heat pump is assumed to have a maximum capacity of $\overline{P_{hvac}}$ = 800W and the ramp limit is such that from one time-step to the other the heat pump can completely switch off or on. We observe the operation of the heat pump for a period of 10 days. The time period of each time-step is one hour. In the base case, we assume that the cost of operating the heat pump is a constant value and is set at €45/MWh. As our case study is defined as a linear programming problem, the simulations are executed using the GLPK solver through the Pyomo package [17] provided in Python 3.7.

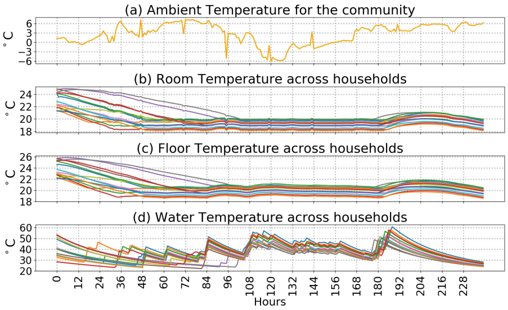

Fig. 2: Base case values for (a) Ambient, (b) Room, (c) Floor and (d) Water Temperatures

From the operational profile of the heat pump, it is observed that it is operated in a way such that it compensates for any heat that is lost by the room to the ambient surroundings. Figure 2 provides information on the temperature profiles for each household. The ambient temperature for the community is presented in Figure 2(a), and the variations in room, floor and water temperatures are presented in Figures 2(b) - 2(d). From Figure 2 it can be observed that initially the heat transfer will take place between mediums till a thermal equilibrium is reached. There on forth, the heat pump will operate by increasing the temperature of the water which is then propagated to the room thereby maintaining the thermal equilibrium with the ambient surroundings. This equilibrium is achieved at the lower bound of the consumer temperature preference.

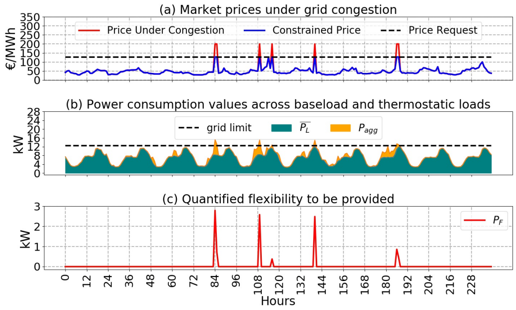

Fig. 3: Determining flexibility required for constraining prices (a) Market Prices, (b) Load Profiles and (c) Flexibility Needed

Next, we compute the community wide aggregated thermal demand. This is presented in Figure 3(b) as P_{agg}. The baseload profile is obtained from [18] and consists of the load profile $\overline{P_L}$ for an average household in the Netherlands without heating demand. Prices for the electricity market is obtained from the wholesale market [19]. In Figure 3(a) we present the electricity prices over a 10 day period for January 2017, the price spikes due to congestion and the constrained prices assuming that the price limit specified by the community is $\overline{\lambda^*}$ = €128/MWh . The grid limit is set to 12.5 kW and is illustrated in Figure 3(b) along with the baseload and thermal loads. Then with the DSO executing Equation (1), we determine the flexibility required for constraining price, and its quantification is presented in Figure 3(c).

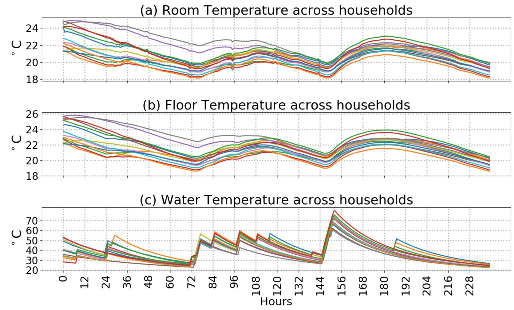

Fig. 4: Reduced Load case values for (a) Room, (b) Floor and (c) Water Temperatures

In order to evaluate the potential of the heat pump to satisfy the flexibility requests, Equation (4) is executed. These results are presented in Figure 4. The heat pump is now responsive to time-varying price and has deterministic knowledge over the entire simulation period. Hence, it can be observed that in response to the variations in ambient temperatures, the heat pump operates such that it preheats the water in the tank when electricity prices are low as can be observed in Figure 4(c). This heat is then eventually conducted to the room. Thus by exploiting the thermal inertia of the dwelling, thermal load consumption can be moved to periods of low prices.

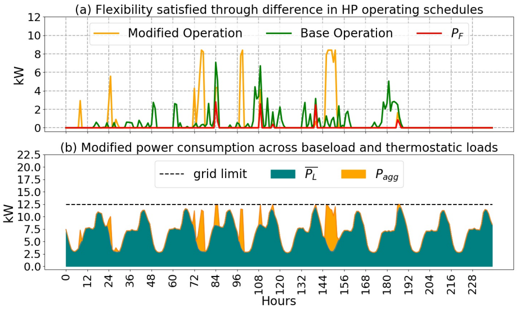

Fig. 5: Load (a) comparison and (b) profile for modified TCL

In Figure 5(a) the aggregated thermal load is compared against the reduced load case. It can be observed that during periods of price spikes, an aggregator by controlling the heat pump can reduce the thermal load thereby constraining the prices and effecting the hedging functionality. The aggregator can then propose the new heat pump operational profile to the DSO. In return, the DSO can coordinate with the aggregator to dispatch the load while taking into consideration that no grid violation is incurred. In Figure 5(b) the combined baseload and thermal load profile is presented.

V. CONCLUSION

In this paper a mechanism for constraining local electricity prices using demand-side flexibility is explored. We have investigated the potential of thermostatically controlled to provide the required flexibility to hedge against price spikes. In our simulation, price spikes occur for a period of 6 hours over a 10 day period. With the proposed formulation and coordination mechanism between actors, the community as a whole could realize a saving of 36% over the simulation period. It is expected that with further electrification of the heating sector, the frequency of grid congestion issues are expected to increase, and thus the proposed formulation will provide increased consumer benefits.

Results generated in this paper can be extended in several new directions. First, the information forecasts over the simulation period are assumed to be completely deterministic. In future work, we will explore how different sources of responsive demand such as energy storage and controlled electric vehicle charging can be used together with thermostatically controlled loads to provide the required flexibility. Furthermore, uncertainties arising from ambient temperatures, dwelling parameters or consumer temperature preferences in a probabilistic manner can be considered. Additionally, the formulation can be extended for more resistive networks, characteristics of low voltage distribution grids, by integrating the formulation with a linear approximation of the ac power flow.

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