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A two-part dynamic pricing policy for household electricity consumption scheduling with minimized expenditure

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ABSTRACT

In this paper we propose an optimization model for scheduling electrical appliances for an individual household. Here, customers are offered dynamic prices which are a function of that household's planned consumption and forecasted grid load. We consider a grid connected system with a battery and an in-house renewable energy generator in the proposed scheduling model. This model minimizes the customer's electricity bill subject to different constraints. We analyze our model with various pricing policies, price ranges and appliance operation windows. We find that the expenditure of the consumer decreases considerably in our model when shifting from flat prices to dynamic prices based on the forecasted grid load and the consumer's individual planned consumption. Considerable expenditure reduction and individual load flattening is achieved with the use of a battery and an in-house renewable energy generator. Also, larger the price range, higher is the load flattening and lower is the expenditure. We show that our proposed pricing policy is beneficial to both consumers and suppliers.

1. Introduction

The optimal scheduling of electrical loads has gained considerable research interest with the introduction of dynamic pricing in the electricity sector. Consumers can be encouraged to shift their electricity consumption from higher tariff periods to lower tariff periods in a dynamic pricing policy. An optimized load scheduling model can reduce the consumer's bill without reducing the total consumption. Such a policy can also benefit the supplier by producing a flattened load curve caused by the shifting of some of the load from peak-periods to off-peak periods. As we require high capital investment for capacity addition, reduction of peak demand through dynamic pricing will enable power plants to postpone huge capital investments. Similarly, an increase in the off peak load prevents the existing generating units from being underutilized and makes their usage more economical. The flattening of the load profile is specifically important in developing countries and emerging economies where the investment can be better used elsewhere by postponing capacity addition in the power sector.

Scheduling the operation of too many appliances without a scheduling model is difficult for any consumer particularly when there are frequent price changes. So a scheduling algorithm with suitable supporting automation technology (like smart meters) is required to optimally schedule the load. Thus the successful implementation of demand side management in electricity will require scheduling algorithms to automate the optimized scheduling of appliances. The motivation for this study comes from the need for reduction of expenditure of individual consumers and flattening of individual load profile along with the promotion of the use of energy storage and renewable energy generation at the household level. Thus we present a mathematical model and propose a pricing policy that can minimize the electricity expenditure of the customer and flatten the individual household load at the same time. Our aim is to also promote the use of household energy storage and renewable energy based generators.

Load scheduling optimization models can be developed for different types of dynamic pricing policies or other demand management approaches like consumption limit controls. If the same price points are offered to all grid-connected households, all of them will, in all likelihood, shift their individual load to the low-priced periods. Such mass response will just shift the aggregate peak demand to the low-priced period instead of flattening the load curve. In order to achieve grid load flattening, a scheduling algorithm should either consider all grid connected households or focus on flattening the load of every individual household connected to the grid. Our scheduling model is for an individual household and offers real-time prices that are highly dependent on that household's planned consumption. Thus it helps in flattening the individual load. In this process every household may

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experience a different price at the same time. The use of energy storage systems and in-house renewable energy generation systems (like roof-top solar panels or roof-top wind turbines) in the schedule further minimizes the cost to the user and flattens the load profile. Previous research has dealt with some of these aspects individually; however, this is probably the first study that includes all the aspects.

Several aspects like load scheduling, decentralized dynamic pricing, energy storage and renewable energy consumption and sale have been developed in separate models in previous studies [1,4,27,31,16,23,21,8]. However, all these aspects have not been tested simultaneously in one mathematical model. This motivated us to develop one mathematical model for a household that can schedule the appliances in the house using batteries and renewable energy and result in the least possible expense to the consumer, with a decentralized dynamic pricing policy. The novelty or innovation in our model is that it offers a price range to a customer instead of a set of discrete prices, a two-part pricing, a piecewise-linear price function reflecting the customer's planned consumption and household load flattening.

Almost all earlier studies have dealt with dynamic pricing policies where specific prices are provided to the customer at each time slot [5,20,15,18]. Thus all customers of a utility receive the same price signal. We propose that the customer should be offered a price range and a price function rather than specific prices. Thus every customer gets a unique price. Earlier studies have used only one price component in their pricing that relates either to the grid demand or occasionally to individual consumption. As a result, they have captured either overall demand changes or individual demand changes. We have proposed a two part pricing that captures the effect of demand fluctuation at both the aggregate and individual levels. Our paper also enables load flattening at the household level unlike earlier studies where load flattening is considered at the aggregate level. Moreover, individual load flattening will help develop a culture of uniform consumption among customers that can eventually lead to flattening of the aggregate load. In this paper we make the following contributions.

- We introduce the idea of the electricity supplier offering a price range and a two-part localized dynamic pricing policy to the customer.
- The localized pricing is two-part and is based on both the forecasted grid demand and the planned in-house consumption. We consider a linear price curve for the first and a piecewise-linear price curve for the second.
- We present logical constraints in a mixed integer, non-linear scheduling model for expenditure minimization.
- Here we include energy from the grid, consumption and sale of localized renewable energy and battery simultaneously with appliance sequencing to plan for a 24 h time horizon.
- We have created a new load flattening index. We have shown that dynamic pricing is more beneficial to consumers than flat pricing, through our model.

The paper is organized as follows. The introduction is followed by a literature review and then a description of the proposed system. The assumptions are stated next followed by the model formulation. After that the computational complexity and model implementation are discussed, followed by analysis of the model. The results and discussions are presented thereafter followed by the conclusion and extensions.

2. Literature review

Electrical load scheduling models involving dynamic pricing can be used effectively as a demand side management tool. In our literature review paper [9], we have surveyed 109 papers and provided a literature review of 12 papers on consumption scheduling in the 'Consumption scheduling with dynamic prices' section of the paper. The review from this section shows that load scheduling enables electricity expenditure reduction in a dynamic pricing environment. Linear programming, mixed-integer linear programming and heuristic methods have been used for model formulation in different papers. Some papers have used thermostatically controlled loads while some have classified the appliances according to their operation characteristics. Some papers have an expenditure minimization objective while some include a comfort maximization objective. There are papers that deal with appliances as the only components of the system while there are other papers that include energy storage or/and renewable energy based generators. An idea of team optimum, or more precisely, inclusion of a number of households in the scheduling process, is also mentioned in some papers. The review shows that suppliers and society also benefit from such load scheduling. We reviewed more papers in this current review which are discussed below.

The objective of a scheduling model is mainly expenditure minimization as in [19] where the multiple knapsack problem is used with day-ahead variable peak pricing. Another objective can be comfort maximization, which is generally used with thermal appliances by controlling their temperature output within comfortable limits. An example of comfort maximization is [29] where customer preference is translated into a time-varying priority curve. Comfort can also be enhanced, in another sense, by reducing the waiting time of appliances as in [24] where a framework is proposed for optimal residential energy consumption scheduling which aims to achieve a trade-off between minimizing expenditure and minimizing waiting time for the operation of each appliance.

The price uncertainty while scheduling needs to be dealt with as in [7] where a fast and flexible two-step appliance commitment algorithm is presented. Determining the price through optimal bidding can be a good option as described in [10] where the risk management of a grid-connected residential microgrid is addressed. A price scheme induces a better response in a scheduling process if prices are dependent on actual consumption. [12] compared TOU pricing and a TOU with grid power consumption dependent pricing function. Expenditure is minimized here by heuristics. Price is calculated locally based on the consumption history, grid load and customer type in [27]. Here a self-organized real time price is calculated based on grid frequency, in real-time. Instantaneous load billing based on grid demand is developed using game theory in [3]. This model allows information sharing among neighbors to achieve minimum costs for all customers.

One of the benefits of a scheduling process is flattening of the household load profile as shown by [6]. The flattening is described here in terms of the load-leveling effect and the peak-load ratio. The scheduling process sometimes requires sequencing of appliances as in [2]. A consumer's benefit is maximized by adding a battery to the system and scheduling its charging, discharging and standby activities as in [30]. The use of renewable energy based generators also enhances the consumer's benefits. This can be seen in [33] where several load schedules having different costs and robust levels are developed with uncertain solar energy and dynamic pricing. There are several research works that highlight the usefulness of load scheduling optimization models in a system with battery energy storage and renewable energy supply within a typical dynamic pricing scheme like time of use pricing or real time pricing [25,28,32,13,14,22,26]. Research on hardware for such systems is also available like [17] where a bidirectional converter device is described, whose control system can operate to follow load shifting programs and can be used to inject power back to the grid.

We have identified that a two-part and decentralized pricing scheme has not been studied earlier. Also, it is likely that nobody has worked earlier with mixed integer non-linear programming with logical constraints. We have presented our literature review in Table 1 where our contributions in this paper and the differences from earlier work have been highlighted.