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Estimating the benefits of cooperation in a residential microgrid: A data-driven approach

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HIGHLIGHTS

- Demand response puts pressure on energy providers to consider new pricing schemes.
- We introduce cooperative demand response. It can cut energy bills by 10%.
- A capacity-pricing component can encourage reductions in peak demand.
- Cooperative demand response can benefit consumers and energy providers alike.

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ABSTRACT

Private households are increasingly taking cooperative action to change their energy consumption patterns in pursuit of green, social, and economic objectives. Cooperative demand response (DR) programs can contribute to these common goals in several ways. To quantify their potential, we use detailed energy consumption and production data collected from 201 households in Austin (Texas) over the year 2014 as well as historic real-time prices from the Austin wholesale market. To simulate cooperative DR, we adapt a load-scheduling algorithm to support both real-time retail prices and a capacity-pricing component (two-part pricing schemes). Our results suggest that cooperative DR results in higher cost savings for households than individual DR. Whereas cooperative DR that is based on real-time pricing alone leads to an increase in peak demand, we show that adding a capacity-pricing component is able to counteract this effect. The capacity-pricing component successfully reduces the cooperative's peak demand and also increases the cost savings potential. Effective peak shaving is furthermore only possible in a cooperative setting. We conclude that cooperative DR programs are not only beneficial to customers but also to energy providers. The use of appropriate tariffs allows consumers and suppliers to share these benefits fairly.

1. Introduction

There is a strong imperative for us to alter the way that we use energy [1]: High levels of carbon emission, a growing opposition to nuclear power in response to the 2011 reactor melt-down in Fukushima, and technological advances have led to a shift towards renewable energy sources (RES) in many countries. However, the intermittency of RES creates considerable stability challenges for energy providers and grid operators. Grid management presents additional challenges in that electricity networks themselves are increasingly being recognized as major sources of carbon emissions and need to be structured and operated in a more environmentally sustainable manner [2].

Centralized demand-driven energy systems that reactively balance supply against demand at all times are no longer able to cope with these challenges. Conversely, decentralization and the use of microgrid structures has been identified as a more viable alternative [3]. Microgrids serve as a platform for balancing demand and supply and they emphasize the idea of organizing and optimizing electricity networks locally [4]. Microgrids can be managed by commercial entities or even by retail consumers themselves via *energy cooperatives* [5]. These cooperatives offer a maximum level

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of flexibility in terms of ownership structure as they are able to handle conflicting interests of different stakeholders [4]. Although in Germany, for example, energy cooperatives are considered to be important building blocks in the transition towards more sustainable energy systems, there is surprisingly little in the literature on their practical potential [6]. Energy cooperatives can allow households to collectively optimize their energy systems and reduce their external dependencies, and can provide opportunities for effective *demand side management* (DSM). In general, DSM includes energy conservation efforts, energy efficiency measures, and *demand response* (DR) programs which encourage changes in electricity usage via price or grid management signals [7–11]. In this paper however, we only focus on demand response.

The idea of turning demand into an additional degree of freedom of the grid is not new. DR has been commonplace in the industry and commercial sector for more than 30 years [12]. However, developments in smart metering technology and the introduction of smart appliances have increased interest and research in residential DR. Consequently, recent years have seen considerable advances in both smart devices and operational concepts for residential DR. However, the role of choice and the human dimension of energy use have been downplayed in energy research [13]. Consumers do not change their consumption patterns unless they see benefits from such a change. A 2008 survey of 2900 households in five European countries (Austria, Germany, Italy, Slovenia, and UK) suggests that the general acceptance rate for smart devices is above 80%, but that consumers expect a perceptible economic benefit from contributing to load management in energy systems [14,15]. In other words, energy providers need to buy flexibility from their customers [16]. More recent studies on smart grid adoption suggest that acceptance levels are also increasingly driven by social norms and environmental concerns, but that financial benefits, i.e. lower electricity bills, still remain the most fundamental motivational factor [17–19].

Reservations to DR can still outweigh these factors, if DR programs are either too complex [20] or if cost savings fail to meet expectations [21]. In this context, Gottwalt et al. [22] calculate that, for individual consumers who do not engage in microgeneration, the savings from time-based tariffs and DR are rather low and are largely offset by the costs of acquiring smart devices. They therefore question whether the financial incentives are sufficient to encourage households to participate in DR. Feuerriegel et al. [23], however, argue that the real economic benefits of DR remain to be quantified, yet they only approach this evaluation from the limited perspective of an electricity retailer. One of their findings is that electricity retailers gain an immense advantage from DR while the average savings for the individual consumer are relatively small. Thus, the main objectives in this study are to quantify the economic benefits from the customer's perspective, to determine what additional economic potential energy cooperatives can provide, and to identify how a more widespread adoption of microgrid structures and residential DR can be encouraged.

To tap into the full economic potential of DR, previous studies have proposed a variety of control mechanisms that are most often tailored to single households. Rastegar et al. [24] e.g. present an one-household mixed integer linear programming (MILP) approach incorporating smart devices, photovoltaic (PV) generation, storage, electric vehicles, and a time-of-use pricing scheme. A similar MILP model formulation that additionally incorporates load peak limitations is presented by Erdinc [25]. These two mechanisms generate a single up-front schedule for the entire planning horizon, which makes them interesting for an evaluation study yet rather unsuitable for dynamic operational implementation. Conversely, Di Giorgio and Pimpinella [26] propose a MILP model for event-driven real-time scheduling. Their idea is to rerun the model, i.e. reschedule appliance execution times, whenever there is a change in the environment, such as improved forecasts or user interaction. An extension of this work also focuses on prosumers by including distributed generation (DG), storage units, and electric vehicles (EV) [27]. Although all these mechanisms can offer considerable energy bill savings, none of the authors aim for a comprehensive evaluation of the actual economic potential.

While beneficial to consumers, individualistic DSM approaches are not ideal for the grid. By design single-household mechanisms attempt to cut individual electricity bills. This can cause a herding phenomenon, when all consumers shift their loads to periods when prices are low, generating new demand peaks [22]. However, introducing centrally coordinated peak control measures comes a considerable electricity costs for individual consumers [26–28].

An alternative to single-household approaches are multiple-household DR schemes. These mechanisms generally follow either a decentralized or a centralized DR control paradigm [29]. Decentralized mechanisms do not have direct access to residential loads. Instead, they try to encourage households to behave in a mutually beneficial way. Ramchurn et al. [30] show that, in principle, globally optimal results are possible even without explicit coordination between households, as long as all households follow the same DR approach and do not readjust their load schedules too often. Veit et al. [31] on the other hand opt for explicit coordination via a dynamic pricing mechanism that presents consumers with personalized prices in order to incentivize beneficial load-shifting. These personalized prices effectively discourage suboptimal herding behavior. The authors set up an extensive case study to establish the economic potential of coordination but the mechanism often fails to provide feasible solutions.

Centralized DR approaches are more robust as they do not require iterative coordination. They transfer control from the individual household to a single overarching mechanism. Conceptually, these approaches best reflect the idea of an energy cooperative that centrally manages its own microgrid. Centralized approaches have been proposed for scenarios with and without microgeneration. Bradac et al. [32], for example, introduce a multi-household MILP model for consumers that do not own power generation systems. They indicate that their mechanism can generate considerable economic potential but do not support their results beyond exemplary appliance data. Zhang et al. [33] include shared RES and propose a MILP to minimize the energy cost of a microgrid that consists of a single smart apartment building. Based on illustrative appliance usage patterns they show that cooperative scheduling can reduce electricity costs by at least 11% compared to not using DR. However, they do not verify these findings for actual historic consumer behavior.

Multiple-microgrid management integrates several microgrids that might have differing objectives. Velik et al. [34] propose such a multi-objective strategy that enables the integration of microgrids with environmental and economic objectives. Although not explicitly considering DR, they find that cooperation between economically and environmentally oriented parties can be beneficial to both, regardless of their differing goals. Even without DR, cooperative behavior can thus be worthwhile for higher grid management levels as well.

Given the growing importance of residential DR, and especially the key role of financial stimuli, our work is intended to provide a realistic estimation of the cost savings that cooperative DR can offer today. As data from cooperative pilots is not yet available, previous research has suggested smart grid simulations to test cooperative DR in a risk-free environment [35,36]. We thus introduce a simulation framework for a residential microgrid and fit it with historic load and price data. The modelled microgrid connects several homes, each equipped with various household appliances and some homes additionally own EVs and/or photovoltaic panels. These homes employ a MILP mechanism to collectively optimize