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Cooperative electricity consumption shifting

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ABSTRACT

In this paper, we propose the formation of agent cooperatives offering large-scale electricity demand shifting services, and put forward a complete framework for their operation. Individuals, represented by rational agents, form cooperatives to offer demand shifting from peak to non-peak intervals, incentivized by the provision of a better electricity price for the consumption of the shifted peak load, similar to economy of scale schemes. We equip the cooperatives with a novel, directly applicable, and effective consumption shifting scheme, that allows for the proactive balancing of electricity supply and demand. Our scheme employs several algorithms to promote the formation of the most effective shifting coalitions. It takes into account the shifting costs of the individuals, and rewards them according to their shifting efficiency. In addition, it employs internal pricing methods that guarantee individual rationality, and allow agents with initially forbidding costs to also contribute to the shifting effort. The truthfulness of agent statements regarding their shifting behaviour is ascertained via the incorporation of a strictly proper scoring rule. Moreover, by employing stochastic filtering techniques for effective individual performance monitoring, the scheme is able to better anticipate and tackle the uncertainty surrounding the actual agent shifting actions. We provide a thorough evaluation of our approach on a simulations setting constructed over a real-world dataset. Our results clearly demonstrate the benefits arising from the use of agent cooperatives in this domain.

1. Introduction

Electricity is undoubtedly one of the most important commodities in our world, affecting almost every aspect of daily life, from industrial production processes and commercialism, to people's heating, well-being and recreation. Existing systems for electricity generation mainly produce electricity by the burning of fossil fuels. Apart from the fact that their sources are depleting, their use is harmful to the environment as their extraction might harm surrounding areas, and their burning produces gases which help exacerbate the so-called "greenhouse effect".

As a remedy for these concerns, recent trends propose "greener" approaches that will help future electricity production become less polluting, introducing the hope for a more sustainable development [1–3]. The emerging *renewable energy* generation sources can be organized in a non-industrial and decentralized manner, allowing the average household to contribute and benefit from its participation to the electricity production process [4,5]. Despite the positive effects from using renewable energy sources, new challenges arise for electricity production and demand management. This is because weather-dependent electricity sources are by definition intermittent, and potentially unreliable regarding their output size.

Against this background, the contemporary *Smart Grid* agenda of research aims to create a more secure, reliable and efficient electricity networks infrastructure, with energy produced mostly by "green" sources, production costs minimized, and affordable electricity made easily and reliably available to the public [6,7,1]. Now, due to the scale and complexity of electrical networks management, artificial intelligence (AI) and multiagent systems (MAS) solutions are in high demand in the emerging markets involving business entities providing Smart Grid services [8,3]. Many such entities have already adopted a business model that pulls together the resources and abilities of multiple economically-minded individuals. Specifically, the emergence of *virtual power plants (VPPs)* or *cooperatives* of small-to-medium size electricity producers, consumers, or even prosumers[1] – that operate as a virtually single entity – has been hailed as a means to create large, efficient,

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[1] A prosumer is an entity that both produces and consumes energy.

trustworthy providers of renewable energy production or electricity consumption reduction (peak-trimming) services [8–11,3,12]. VPPs can also deliver a range of *demand side management (DSM)* services. In DSM, consumers contribute to the stability of the electricity grid in exchange for certain, usually monetary, rewards. DSM services can be loosely divided into three categories: consumption reduction programs, load management programs, and energy conservation programs [13,10,14]. Now, although reduction and conservation can obviously contribute to the reliability and sustainability of the power system, they require large investments for equipment and infrastructure upgrade [15]. Moreover, these efforts can reach a maximum effectiveness level, beyond which further reductions cannot be tolerated, because such actions begin to interfere with consumer comfort and well being [16]. In any case, any DSM technique should make sure that consumer needs are accommodated and consumer tasks are eventually completed—even at earlier or later times than originally scheduled. Furthermore, load-management schemes are an alternative to *electricity storage*—a problem difficult by its nature, and the tackling of which requires the use of expensive equipment [17].

In this paper, we take the provision of electricity load management solutions one step forward, by proposing the formation of *agent cooperatives for demand shifting services*. In particular, our work demonstrates how to perform *large-scale, collective electricity consumption shifting*. To the best of our knowledge, ours is the first ever complete mathematical framework for collective electricity consumption shifting, which comes with several desirable properties and guarantees, and which is also evaluated extensively via simulations on a real-world consumption dataset.

Our scheme motivates self-interested business units, represented by autonomous agents to join forces in a cooperative and shift power consumption from peak intervals to others with lower demand, in order to receive lower electricity price rates for their contribution. This is similar to economy of scale approaches, where groups of buyers join together to finally buy larger good numbers at a better price each [18,19]. Consumption re-scheduling can be performed a day-ahead, thus avoiding the dangers and risks of last-minute action. In this way, our scheme *proactively balances future supply and demand*, without any losses affected to the utility of the contributors.

Now, for the cooperative to be successful at *large-scale* shifting effort, it is obvious that *coordinated joint shifting efforts* have to take place, carried out by *demand shifting coalitions*. Inspired by work in the *cooperative games* and related MAS literature [20], we propose several methods for the formation of shifting coalitions. These *coalition formation* methods group together agents based on criteria such as their perceived shifting contribution potential, and their expected economic gains from participation. We also devise *internal pricing* mechanisms that determine *variable*, and *individual-specific* reduced electricity prices for our agents, via implementing *expected gain transfers* among the coalescing consumers. The resulting *internal price balancing* incentivizes even agents with initially forbidding shifting costs to participate in the cooperative effort.[2] We put forward several such internal price balancing techniques: a heuristic mechanism; and five alternative ones. All of our proposed internal pricing methods satisfy budget-balancedness.

Thus, our mechanism employs coalition formation and internal pricing techniques in order to facilitate the shifting of sizeable electricity consumption amounts from peak to non-peak time intervals. The effectiveness of the joint coalitional shifting actions naturally depends on the accuracy of the members' statements regarding their shifting capabilities, and their confidence about meeting their forecasted goals. These statements, however, might not be accurate forecasts, as consumers might not be able to accurately predict their shifting capabilities, or are not truthful (due to low trust towards their partners, or similar concerns). Therefore, to promote truth-telling and efficiency in load shifting, we employ a *strictly proper scoring rule*, the *continuously ranked probability score (CRPS)*, proposed in the mechanism design literature [22]. The use of *CRPS incentivizes* agents to truthfully and precisely report their predicted shifting capabilities.

Of course, even if participating agents are perfectly truthful regarding their abilities and corresponding uncertainty, their reports and estimates can still be highly inaccurate. This can be due to, for example, communication problems, malfunctioning equipment, or prejudiced beliefs and private assumptions—e.g., a truthful reporting agent might be overly pessimistic or optimistic. As a result, monitoring the performance of individuals and correctly predicting their future contributing potential is of utmost importance to any organization relying on the services of selfish, distributed, autonomous agents. To this end, several approaches try to explicitly estimate agent electricity consumption and production amounts, by incorporating prediction models that rely on agent geographical location and weather forecasts, or the processing of macroeconomic data [23,24]. However, such methods cannot immediately predict the actual behaviour of a specific agent, which might be motivated by private knowledge or business concerns, neither do they account for errors due to equipment malfunction. By contrast, here we propose the application of *generic* prediction methods, which are nevertheless able to adapt to a specific agents behaviour and generate accurate estimates. In particular, we propose the use of stochastic filtering methods to keep track of the parameters that best describe agent behaviour, and to effectively predict future agent performance.

An extensive experimental evaluation of the proposed mechanisms and methods was performed on a large dataset containing real consumption patterns from the Kissamos district at western Crete, Greece. Our experiments confirm that granting a low enough price to the consumers incentivizes cooperative consumption shifting—as long as this price allows the agents to (collectively) overcome their shifting costs. Moreover, our results indicate that the coalition formation method that yields the best results with respect to load shifting effectiveness and actual monetary gains for the participants, is one that creates agent coalitions that maximize in expectation both the eligible amount for shifting, and the expected gains of their members. We also assess the behaviour of the various internal pricing methods we propose, and conclude that our heuristic price balancing approach, in particular, is the most appropriate for use in this domain. Further, we demonstrate that employing *CRPS* is effective: inaccurate agents suffer penalties that are higher than those of their more accurate counterparts, and individual agents and coalitions alike are incentivized to be truthful and accurate regarding their stated shifting capacities. Finally, our experiments show that employing stochastic filtering techniques for agent performance monitoring improves our mechanism's effectiveness and quality. In particular, we show that stochastic filtering leads to greater (near 100%) accuracy *wrt.* forecasted shifting performance; higher collective peak consumption reduction; and increased financial gains for the shifting cooperative.

Summing up, our work here provides several contributions to the state of the art. This is the first time that a complete framework for effective large-scale demand shifting is provided in the literature. We propose a variety of novel coalition formation methods that can be used by consumers wishing to join forces

[2] This is similar to group purchasing in e-marketplaces, where agents collectively get better prices for their purchases; and where, due to group-internal price fluctuations set by corresponding mechanisms, the purchase finally becomes advantageous to all—even though some members would not be able to obtain the items even at the better rate promised [21,19].