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Game-theoretic approach to demand-side energy management for a smart neighbourhood in Sydney incorporating renewable resources

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HIGHLIGHTS

- Optimization based load and DER scheduling model is presented based on Nash game theory.
- An improved game theoretic DSM framework has been developed to provide cost saving and PAR reduction.
- Novel Real time tariff model based on historical and predicted wholesale prices is developed.

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ABSTRACT

Recent developments in smart grid technologies have enabled interactions between energy suppliers and consumers, leading to profits made by both parties via Demand-side management (DSM). Demand-side management enables consumers to control their energy profile to reap economic benefits. It also helps energy providers to reduce the peak average ratio (PAR) by leveraging the flexibility of distributed energy resources (DERs) and renewable-energy resources (RESs) to supplement grid power, thereby avoiding the use of expensive peak-power plants. This paper presents an improved game-theoretic DSM framework for a neighbourhood area to provide cost savings for the consumer and reduce the PAR for the neighbourhood. The proposed DSM framework utilizes the flexibility of DERs and RESs to allow energy sharing among neighbours to reduce the demand peaks. A novel real-time price (RTP) retail tariff model has been established based on historical and predicted wholesale prices. A Nash-game-theory-based optimization model is developed for scheduling the building loads and DERs. The optimization model minimizes the energy cost to the consumer while maintaining an optimal comfort level for the consumer and satisfying consumption constraints to reduce peak demand. The proposed DSM framework and optimization model is verified via case studies with real building consumption data for a neighbourhood in Sydney, Australia. Game-theoretical analysis ensures that users do not make profits if they deviate from their assigned consumption pattern. The performance of various algorithms is evaluated and their effects on the peak average ratio (PAR) and energy costs are discussed. The effectiveness of the proposed game-theoretic optimization model is validated and compared with traditional non-game-theoretic models. The results of the proposed algorithm show reductions in the peak average ratio of the community and the cost incurred by the consumers. The PARs of the game-theoretic approach during summer and winter are 1.76 and 1.81 respectively. The cost reduction of the game-theoretic model is 9.17% during summer and 9.68% during winter compared to the non-cooperative approach. The numerical results represent the efficacy of the proposed DSM model in reducing the PAR of the community and the energy cost to the consumer.

1. Introduction

Recently electricity demands have been on the rise due to massive developments in different countries including Australia. This increase in demand can be attributed to changes in the consumption pattern of buildings, since a third of the energy generated is consumed by buildings. These raise concerns over energy generation and supplies, resource depletion and bridging the gap between generation and demand. This increased gap between supply and demand needed the infrastructure to become smart by employing sensors, processors and automation. This in turn improves energy efficiency and ensures optimal utilization of energy resources. The influx of distributed

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Nomenclature

c	index for consumers (c = 1, 2, 3, ...,$\mathbb{C}$)
$\mathcal{M}$	total number of shiftable loads
$\mathcal{N}$	total number of non-shiftable loads
m	index for shiftable appliances (m = 1, 2, 3, ...,$\mathcal{M}$)
n	index for non-shiftable appliances (n = 1, 2, 3, ...,$\mathcal{N}$)
$\mathcal{E}$	energy consumption vector of appliances
t	time period (30 min)
$\mathcal{H}$	total simulation time
$\mathcal{L}$	total number of loads
$\mathbb{C}$	set of consumers
x	consumption scheduling vector of shiftable appliances
y	consumption scheduling vector of non-shiftable appliances
$\mathcal{X}$	consumption scheduling vector of all loads
ψ	appliance operation start time
ω	appliance operation end time
$\mathcal{P}^t$	total power consumption of the community
$\mathcal{P}_g^t$	total power generated by RES
$\mathcal{P}_m^t$	total power consumed by shiftable appliances
$\mathcal{P}_n^t$	total power consumed by non-shiftable appliances
α_m^t	control variables for shiftable loads
α_n^t	control variables for non-shiftable loads
p	pay-off function for a consumer
z	set of actions for a player in the game
w	daily electricity charge to consumers

generation by individual buildings or communities, electro-mobility and the fluctuations in weather create an uncertainty in the power to be supplied from the grid. The smart grid adds monitoring, control and communication capabilities to increase the efficiency and profit. Demand-Side Management (DSM) and energy-storage systems can be used to mitigate the fluctuations caused by renewable-source generation. Many studies have been carried out to show the effectiveness of DSM with renewable energy and real-time pricing. Researchers in [1] argue that demand shifting increases a user's consumption of renewable energy by approximately 5.8% for every 10% saved on the user's average unit electricity price. Although DR and DSM are popular there exist many challenges to their deployment, the major being the uncertainty in their value [2].

Smart energy expresses an approach that is much broader than the smart grid. There is a shift from a single sector to coherent energy systems which involves the understanding of the design, analysis and benefits of integrating a large community [3]. DSM generally refers to those activities implemented to improve energy efficiency and reduce the cost at the customer side and control the energy consumption without having an impact on the comfort of the consumers. These activities include the use of smart meters, real-time tariffs, incentives that aid in reducing consumption at certain periods, proper resource allocation and control methodologies and load control by an external controller. The end-consumers play an active role in the successful implementation of DSM techniques. Consumers are ready to participate in adopting DSM strategies if such methodologies maximize their satisfaction within their budget [4]. The proper use of DSM techniques will aid in the reduction of the Peak-to-Average Ratio (PAR) and the peak demand. DSMs offer a less expensive approach to influence a load than installing a new power plant or storage devices [5]. The selection of proper appliances with higher star ratings helps in reducing energy consumption. Appliances that consume more energy such as a heat pump could be coupled with thermal-energy storage systems and integrated with renewable sources, so that they are economically feasible and provide a promising technology for load management [6,7]. The researchers in [8,9] have provided an economic analysis and have shown that the horizontal ground source heat pump is more economical than conventional heating methods and the ground-coupled heat pump is economically viable over the air-coupled heat pump system.

The use of renewable energy as an alternative is gaining momentum with governments issuing rebates and incentives to consumers who install them. Many studies have been conducted on the technical feasibility of sustainable heating through renewable energy sources [10]. The Australian Renewable Energy Agency (ARENA) and the Australian Energy Market Operator (AEMO) jointly announced 10 pilot projects worth $ 35.7 million in late 2017 to implement DSM. This DSM project aimed at freeing up 143 MW in the summer of 2017 and 200 MW of capacity by 2020. Funds were allotted to energy retailers and distributors, a DR aggregator, a smart thermostat developer and a metal foundry [11]. The incentives gained in using DERs and the introduction of communication capabilities into power networks have aided the restructuring of the electric-power industry [12]. The two-way communication capabilities of smart grids, and their ability to predict and share data and the implementation of real-time pricing, has enabled the implementation of DSM easier. Consumers could be effectively convinced to shift their peak-time loads to off-peak periods [13]. In real-time pricing schemes, the energy price for a certain period is proportional to the aggregated load during the considered period. Typically, a consumer who follows real-time pricing (RTP) might expect that, by curtailing or shifting their energy use for a few hours a year, they might be able to avoid the surge prices and so experience an average reduction in cost of about 10–20%. The billing mechanism is equally important to the success of DSM as it acts as a motivation to consumers to adopt DSM. DSMs can be more effective if the energy generated can be stored on site and the predicted cost functions are accurate.

In DSM programs, the controller can remotely manage the operation of controllable appliances so that energy savings are obtained. In such direct-load-control (DLC) schemes consumers receive incentives and allow companies to control some of their loads at certain periods. Shiftable appliances are those whose operation can be shifted to other time periods without a compromise in the comfort setting of the consumer. Those appliances may include a dishwasher, washing machine or a plugin electric vehicle (PEV). The consumption of these appliances needs to be predicted and their effects on DSM has to be investigated. The proper implementation of DSM techniques envisages a need for interaction between the utility and the end-consumers in such a way that both the utility and the consumer benefit. Authors in [14] discusses a Multi-Agent System (MAS) based Home Energy Management System (HEMS) comprised of a scalable market-based architecture to provide network support functionalities during congestion and over-voltage. A scheduling problem formulated as a mixed-integer linear-programming problem (MILP) with grid reliability criteria constraints is discussed in [15]. It minimizes energy consumption with an optimal comfort level, but fails to address the economic aspect of schedule shifting.

Load management algorithms become effective if the participating parties take a coordinated decision. This can be either centralized or decentralized. In a centralized system an aggregator or a third party performs the coordination. Although effective, it involves vast data collection and imposes a computational burden on the aggregator. It also poses privacy issues since critical information on the consumer is required. In a decentralized mechanism consumers make decisions with external inputs from an entity or utility. This reduces the computational burden and eradicates the disadvantage of a centralized system in the absence of data from a consumer due to communication failure or device malfunctioning [16]. Attractive policies coined by policy makers attract attention from end users who are less concerned with curtailing load. The policies coined should be in such a manner that the benefits surpass the difficulties to users when curtailing load [17]. A smart grid management by the supplier and an intelligent energy management, "i-Energy" from the customer's side is combined to form a real-time