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Fair cost distribution among smart homes with microgrid

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A B S T R A C T

Microgrid is composed of a set of distributed energy resources (DER) and is considered as an alternative energy providing system to the current centralised energy generation. Smart homes equipped with smart grid technology, such as smart meter and communication system, are becoming popular for their lower energy cost and provision of comfort. Flexible energy-consuming household tasks can be scheduled coordinately among multiple homes which share the common microgrid. When local DERs cannot fulfill the whole demand, smart homes will compete with each other to obtain energy from local DERs and achieve their respective lowest energy cost. In this paper, a mathematical programming formulation is presented for the fair cost distribution among smart homes with microgrid. The proposed model is based on the lexicographic minimax method using a mixed integer linear programming (MILP) approach. One-day forecasted energy cost of each smart home is minimised under fairness concern. DER operation, DER output sharing among smart homes and electricity consumption household tasks are scheduled. Two numerical examples with 10 and 50 smart homes are studied. The computational results illustrate that the proposed approach can obtain obvious cost savings (30% and 24% respectively) and fair cost distribution among multiple homes under given fairness scenario.

1. Introduction

The energy consumption increases along with population size and the price of fossil fuels has increased quickly during the last decade. Energy cost and pollution reduction have attracted more attentions than before from most countries [1]. As the energy consumption by buildings represents 30–40% of the world's primary energy consumption while resulting in about 45% of the anthropogenic CO_2 emissions [2], energy supply management to buildings is important to conserve energy and protect the environment. Improving energy efficiency in commercial buildings is discussed in [3] and basic improvement actions in operation are presented. For domestic energy consumption, it depends on the dwelling physical properties, appliances' efficiency and occupants' behavior. 10–30% Energy consumption reduction can be obtained by changing the living behavior [4].

Renewable energy sources are preferred to provide energy production to fulfill the energy demands while reducing the air pollutions. Distributed energy resources (DER) have been proposed and applied for domestic sector. DER is defined as local resource related to the energy system, and considered as an alternative or complement to current centralised energy generation [5]. They are emerging technologies which utilise possible diversification of primary sources of energy in future power systems to reduce economic costs while reducing greenhouse gas emissions. Mehleri et al. [6] propose a mixed integer linear programming (MILP) model for the optimal design of distributed energy generation systems at the level of a small neighborhood. Microgrid is a set of DERs and defined as an electricity distribution network that can be grid-tied or operate autonomously from the rest of the network. Microgrid performance metrics for energy management are presented in [7]. Also various detail pricing schemes, such as critical peak pricing (CPP), time-of-use (TOU) and real-time pricing (RTP), are being designed by utilities through the development in the power system. Together with smart grid technology introduction, they encourage and enable consumers to participate actively scheduling their home appliances to save energy, reduce cost or help grid operation [1,8].

Smart homes are proposed to provide some common benefits to the customers, such as lower energy costs, provision of comfort and home-based health care and assistance to elderly or disabled users [9]. Energy management in smart home can be achieved by scheduling energy resource or energy tasks. Some work has been done to achieve the energy conservation and management perspectives and obtain the minimum operation cost [10–16]. However, only the operations are scheduled based on given energy profile rather than the energy demand itself. Sun and Huang [17] review available energy optimisation methods for energy management in smart homes and work referring scheduling of appliance operation time has also been mentioned.

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More work considers the energy task operation time scheduling. Sou et al. [18] propose an MILP framework for smart residential appliance scheduling with 24-h known electricity tariff. Another work for scheduling the operation of smart appliances is proposed by [19], domestic loads are shifted with RTP to obtain the maximum energy savings. In [20], a peak-load shaving online scheduling framework is presented. There are some recent papers considering the scheduling of both energy generation and loads. Deferrable and no-deferrable tasks commanded by the user are scheduled for one day of a house with PV generation in [21], and the operation of an electrical demand-side management system is provided. Kriett and Salani [22] minimise the operating cost of both electrical and thermal supply and demand in a residential microgrid with a generic MILP model. A RTP based demand response management application is proposed by [23], which determines the optimal operation of the residential appliances of a single house in the next 5-min time interval by considering future electricity price uncertainties. Rastegar et al. [24] present an optimal and automatic residential load commitment framework, which minimises household payment by determining on/off status of appliances, charging/discharging of battery storage and plug-in hybrid electric vehicles. Derin and Ferrante [25] develop a model that considers both operation scheduling and electricity consumption tasks order scheduling. However, only three electricity consumption tasks are scheduled in that work. Zhang et al. [26] present an MILP model to schedule the energy consumption of smart homes in a building, where both DER operation and electricity-consumption household tasks are scheduled based on RTP and given electricity task time window.

All energy management work mentioned above considers either single smart home or a number of smart homes as a whole customer, where only the total energy cost is considered in the objective functions. However, DERs are practically located in a building and shared by all the residents within the building [27]. Residents living in the building would have different living habits and various kinds of domestic appliances in homes, and the energy tasks or task operation times vary accordingly. Each home pays its own energy bill based on their respective energy consumption. They target to obtain their own minimum cost by scheduling their energy task operation time. However, the DERs, which provide cheaper energy, cannot completely supply the demand from all homes eternally. The smart homes will compete with other homes for these cheaper energy resources from DERs during peak demand hours. So, this paper considers how to distribute the costs fairly among smart homes with common DERs in microgrid under competition situation.

Stadtler [28] reviews a number of collaborative planning schemes with different areas of application. Under cooperation and conflict conditions, game theory mathematically describes people's rational decision in obtaining their benefit by considering both their own and other players' decisions. 'Fairness' is not commonly defined and Mathies and Gudergan [29] suggest the definition of fairness as the reasonable, acceptable or just judgment of an outcome which the process used to arrive. The fair solution suggests that all game participants can receive an acceptable or 'fair' portion of benefits. Nash equilibrium and the core are the two dominant concepts in game theory [30,31].

Lexicographic minimax method is another widely used approach to obtain fair solutions. In the lexicographic minimax method, the fairness concept is a refinement of the Pareto optimality. It has been investigated and applied in various areas, such as, bandwidth allocation in computer networks, facility location problems and resource allocation. Lexicographic minimax method originates from the subset selection of optimal strategies from the optimal minimax strategy through the exploit of the opponent optimality mistakes [32]. Lexicographic minimax solution is stated as the nucleolus of a matrix game [33]. Klein et al. [34] develop a lexicographic minimax algorithm to solve a multi-period resource allocation problem. Location problem is addressed by Ogryczak [35] to study the problem of distribution of travel distances among the service recipients. A concept of the lexicographic minimax solution is developed there as a refinement of the standard minimax approach. The lexicographic minimax solution concept for fair allocation is adopted to locate water rights for the demand sites in the Aral Sea region in [36], which solves the problem by an iterative algorithm. Wang et al. [37] apply this concept and develop the lexicographic minimax water shortage ratios approach for modelling water allocation under public water rights regime. [32] apply the lexicographic minimax algorithm for a sensor nodes placement. Erkut et al. [33] employ the lexicographic minimax approach to obtain a fair non-dominated solution from the location allocation problem for municipal solid waste management. This approach is also applied by [38] to deal with the multi-objective optimisation problem of global supply chains in the process industry.

In this paper, lexicographic minimax methods are applied for the fair cost distribution of the smart homes with microgrid. Every player is treated equally and impartially. This work extends the MILP model for smart home electric tasks scheduling in [26], where only the total cost is minimised. An MILP model is proposed here to obtain fair cost distribution amongst participants in a smart building. It is based on the minimisation optimisation approach for the lexicographic minimax method proposed by Erkut et al. [33], which guarantees a Pareto-optimal solution. A fair cost distribution amongst smart homes is determined and each participant will pay a fair energy cost based on their respective energy consumption. The key decision variables consist of: DER operation plan, equipment output sharing plan, task starting time, and energy resources utilisation. In order to demonstrate the applicability of the proposed approach, two illustrative numerical examples are studied; 10 smart homes for a winter day and 50 smart homes for a spring day. The obtained results indicate significant cost savings at the orders of 30% and 24%. Cost is distributed fairly based on the proposed fairness scenario.

The remainder of this paper is organised as follows. In Section 2, the problem is described briefly with relevant assumptions, constraints and objective function. In Section 3, the mathematical programming model is provided. In Section 4, the lexicographic approach minimax for a fair solution is explained. Then in Section 5, the proposed model is applied to two numerical illustrative examples. The computational results are presented and discussed in Section 6. Finally, conclusions are given in Section 7.

2. Problem description

In this paper, multiple homes in a smart building are considered as shown in Fig. 1. A microgrid, which is owned by the home owners cooperatively, is available to provide local energy to the smart homes. The smart homes share common DERs of the microgrid, such as CHP generator, boiler, thermal or electrical storage. Electricity can be obtained from grid all the time when there is no sufficient local energy generated. Surplus electricity generated over the local demand can be sold back to the grid. Each smart home has its own energy (heat and electricity) demands, which depend on the household types, available electrical appliances and living habits. Heat demand for each home is provided according to types of household. While the electricity demand of each home depends on its own daily flexible and non-flexible domestic appliance tasks. Typical flexible tasks include dishwasher, washing machine and spin dryer. Thus, the electricity demand profile depends on the operation time of domestic electrical appliances. It assumes that local controllers are located for each DER and communication system is available to distribute the energy consumption scheme in