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Benefit allocation for distributed energy network participants applying game theory based solutions

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ABSTRACT

This study develops a mixed-integer linear programming (MILP) model integrating energy system optimization and benefit allocation scheme of the building distributed heating network. Based on the proposed model, the minimized annual total cost, energy generators configuration, optimal operation strategy and heating pipeline lay-out of the distributed energy network can be determined. Moreover, four benefit allocation schemes (Shapely, the Nucleolus, DP equivalent method, Nash-Harsanyi) based on cooperative game theory are employed to deal with the benefit (reduced annual cost) assignment among the building clusters, while considering the stability and fairness of each scheme. As a case study, a local area including three buildings located in Shanghai, China is selected for analysis. The simulation results indicate that the ground coalition in which all buildings cooperate with each other by sharing and interchanging the thermal energy yields the best economic performance for the distributed energy network as a whole. In addition, different allocation schemes may result in diversified outcomes in terms of the fairness and stability, which are measured by the Shapley-Shubik Power Index and the Propensity to Disrupt value, respectively. For the current case study, the Shapely value method is recognized to be the most acceptable allocation scheme from both viewpoints.

1. Introduction

Growth in population, enhancement of building services and comfort levels, together with the rise in time spent inside buildings, have raised building energy consumption to the levels of transport and industry [1]. According to EIA (energy information administration), the building sector accounts for around 20.1% of total primary energy consumption worldwide in 2016. An effective alternative method to deal with the increasing energy using in buildings is the adoption of building combined heat and power (BCHP) system [2–4]. As a typical distributed generation system, the BCHP system produces electric and thermal energy simultaneously on-site or near site, and can convert as much as 75–80% of the fuel source into useful energy [4]. The BCHP systems have been introduced into commercial buildings such as hospitals, hotels, offices and so on.

Based on the distributed BCHP system, the generated surplus energy can be shared among the buildings to realize the energy interchange network. In the energy network, to maximize own payoff, a consumer may seek to displace expensive generator by importing energy from neighboring consumers with lower purchasing cost compared with the utility grid. Likewise, a player with excess generator capacity can choose to export energy and receive an immediate return on its initial investment. Therefore, through the distributed energy network, not only the energy performance of the whole system can be improved, but also the unbalance problem between supply and demand sides within each building can be resolved. However, to realize the best performance of a distributed energy network, optimal generator location, management of system operating and energy interacting strategy is critical. Numerous of research has studied the operation of the distributed energy network, for the purpose of energy saving, cost reduction as well as reliability improving. Yang et al. [5] constructed a superstructure based MILP model to achieve simultaneous optimization of capacity, number, and location of energy generator as well as energy distribution network structure of the entire system; two kinds of prime movers (gas engine and gas turbine) were considered as the alternative technology for the BCHP system. Bracco et al.

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[6] adopted a model to optimally design and operate a hybrid heating network in a building cluster equipped with small-size CHP plants, while considering the economic saving and emissions reduction simultaneously. Casisi et al. [7] proposed an optimization model to deal with the optimal design and operation of a distributed cogeneration system with a district heating network while considering the energy saving and emissions reduction at the same time; not only a set of micro-gas turbines located inside public buildings, but also a centralized CHP system based on Internal Combustion Engine is taken into account. Besides the building scale energy network, some studies focused on the district level energy supply system. Obara et al. [8] considered the construction of a Syowa Base energy network, aiming at reducing the fuel consumption and increasing green energy utilization compared with the conventional energy supply system. Weber et al. [9] presented the DESDOP tool to determine the optimal mix of energy technologies for a small city considering distributed energy network, aiming at decreasing the emissions while at the same time guaranteeing the resilience of energy supply.

Summarizing these studies, even though most of them have optimized the energy consumption and/or cost of the whole distributed energy network, how to award the payoff from the cooperation to each player, which is the key question in a cooperation, is paid little attention. If one building can obtain more profits through collaborating with others in some coalition, it will prefer to collaborate to form this coalition rather than act individually, and vice versa. Once the buildings begin to cooperate with others in providing energy demands, the coalition is formed, and all of the consumers can be considered as the multiple stakeholders. Thus, the coordination of their interests is necessary. The purpose of this study is to strive to begin addressing this gap by considering a fair economic settlement scheme for participants in a distributed energy network based on cooperative game theory, which has been widely used to deal with the allocation of cost/gain to incentivize the stakeholders who are cooperating [10–15]. In this study, a MILP model integrating the energy system optimization and benefit (reduced annual cost) allocation scheme of the distributed energy network is proposed and verified through a case study.

The rest of the study proceeds as follows. In Section 2, the framework of the integrated programming model is introduced. Section 3 describes the model for optimal design and operation of the distributed energy network, as well as different profit allocation schemes in detail. Sections 4 and 5 discussed the input data and results of the case study. Finally, several conclusions are deduced and summarized in Section 6.

2. Problem definition

Fig. 1 shows the overall framework of the integrated programming models including the energy supply system optimization model, as well as fair benefit allocation model based on cooperative game theory. In the first model, the input data include energy load, fuel prices, and characteristic data of various alternative technologies. The objective function is to minimize the annual total cost while considering various constraints. Through the first model, the minimized annual cost, optimal running strategy including technology selection as well as heating pipeline lay-out of all possible coalitions can be deduced. Then, based on the output of the first model, four gain/cost assignment schemes, namely the Nucleolus, the Shapley value, the Nash-Harsanyi (N-H) solution as well as Propensity to Disrupt (DP) equivalent method are considered for the allocation of the reduced cost through cooperation of the buildings. Following which, a comparison analysis is included for different allocation methods. Finally, by employing the Shapely-Shubik Power index and DP methods, the fairness and stability of each allocation scheme can be measured. It is important for the participants to decide whether to join the coalition or not. This is because, if the gain/cost allocation is not stable and fair, the cooperation will not persist, the analysis of fairness and stability can thus be helpful for the stakeholders who are making long-term decisions.

3. Mathematical formulation

Generally, in the distributed energy supply network, the electric power demand of each building is satisfied by the BCHP unit if installed, and the deficiency can be supplied by the external utility grid. As to the thermal demand, there are many types of heat resources. The recovered heat from the BCHP unit is one option, backup boiler is another option. Moreover, heat can be interchanged among the building consumers via a distributed heating pipeline and the line distances among the buildings are calculated prior to the optimization. Note that, the cooling demand is also served by the electric power using compression chillers. On the other hand, in order to promote the BCHP unit adoption, the surplus electricity generated can be sold back to the utility grid to make a profit.

3.1. Energy supply system optimization model

The aims of the energy system optimization model include: defining the type and number of BCHP unit in each building, determining the optimal operation strategy of the whole system, as well as deciding the optimal lay-out of the distributed heating network. The objective function is to minimize the total annual cost ($Cost_{tot}$) which consists of annualized initial investment cost ($Cost_{equip}$), the sustained external fuel purchasing cost ($Cost_{fuel}$), the annual maintenance cost ($Cost_{main}$), the annualized energy transfer line cost ($Cost_{dhn}$) and minus profits from the selling of excess electricity to the macro-grid ($Cost_{sal}$), all the year long.

$$Cost_{tot} = Cost_{equip} + Cost_{fuel} + Cost_{main} + Cost_{dhn} - Cost_{sal} \quad (1)$$

Commonly, the energy flows, the equipment characteristics, and the operation mode constitute the constraints in the optimization problem. Hence, the objective function must be minimized subjecting to the following constraints [5,16,17] formulated for each time period:

- The electric and thermal energy input must be equal to the output;
- The performance constraints of the equipment components, e.g. BCHP unit and boiler have to be followed;
- The trade-off constraints with the utility grid, as well as the interchange constraints among the building clusters must be satisfied.

It is worth noting that, the equipment selection and placement from the alternatives, as well as the distributed heating pipeline options are defined as binary variables in the formulas. Based on the concepts introduced above, an energy system optimization model is established, through which the minimized annual cost of each coalition formed by the buildings can be deduced. The detailed information can refer our previous studies [18,19].

3.2. Basic concepts of cooperative game theory

Generally, if there are more than one decision-makers pursuing their own profits at the same time, a decision-making process is called a game. The game theory has been proved to be an effective