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Energy management in Multi-Commodity Smart Energy Systems with a greedy approach

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HIGHLIGHTS

- A general system and a mathematical model for energy management in MC-SES are built.
- A greedy based algorithm is proposed for energy management in MC-SES.
- The greedy algorithm is simulated and compared with the optimization algorithm.

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ABSTRACT

Along with the development of Smart Energy System (SES), the advancing popularity of hybrid energy appliances, such as micro-combined heat and power (CHP) and electric heaters, requires an overall energy management strategy to optimize the energy using while guaranteeing energy supply for both the electricity and heat demand. This paper based on the concept of Multi-Commodity Smart Energy System (MC-SES) proposes a self-sufficient hybrid energy model to minimize the energy exchange with the external electricity grid. Next to the optimization solution for this hybrid energy management problem, a greedy algorithm has been proposed to alleviate the high computational complexity of optimization searching. The optimization, direct allocation and greedy-based methods will all be analyzed, simulated and compared in this paper.

1. Introduction

Development of Smart Energy Systems (SES) typically feature different forms of energy, like electricity, heat and gas. These Multi-Commodity Smart Energy Systems (MC-SES) have to deal with an increasing amount of stochastic power infeed from renewable energy sources as photovoltaic (PV) and micro wind turbines, but also with high penetrations of heavy loads as electric vehicles (EVs) and heat pumps (HPs) [1,2]. Hence, grid operation gets more and more complex in terms of balancing supply and demand and stable grid operation. At the same time, a large part of the energy is consumed by thermal energy demands in Europe [3]. These heating purposes are often associated with great potential in flexibility of energy consumption [4,5]. The thermal flexibility is important for energy management because of the generally large volume of energy consumption and the relatively large margins of acceptable temperature ranges and time of heating. Additionally, the introduction of multi-commodity appliances like electric heaters (e.g., HP or resistive heaters) and combined heat and power (CHP) installations, allows to convert electricity to heat respectively co-generation of energy forms, improving the overall efficiency [6].

Hence, MC-SES should make use of all the energy flexibilities and these hybrid appliances to improve on efficiency, reliability and sustainability of the whole energy system. More specifically, demand side management (DSM) [7–9] and demand response (DR) [10–12] programs can be deployed in the MC-SES to pursue various kinds of objectives, for example, optimizing energy costs, maximizing energy efficiency, minimizing the peak load to average ratio, and local supply and demand matching of energy [11,13–15]. The flexibility in different forms of energy can contribute to more optimal operation of the system via multi-commodity appliances as the CHP and electric heaters. However, most of the previous work in DSM and DR programs mainly focus on the optimization of electricity grid operation and renewable energy efficiency [13,14,16], in which the thermal energy are neglected. In some other works, thermal energy is studied in scenarios with district heating systems, e.g., in [17–20]. In these works, the thermal

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demands and production in households can only exchange energy with the district heating systems, thus, the thermal exchange and flexibility inside single households have not been fully explored. Further, most of the DR programs, which also considering thermal energy, assume that customers can freely participate the electricity market and reacting on the electricity price [21,22], which is not feasible in most of countries.

Therefore, new energy management schemes for MC-SES are needed. To generalize the MC-SES energy management, we adopt the Flexible Power Application Infrastructure (FPAI) [23] that provides the interfaces between energy management and appliances. Based on FPAI and our previous work [24,25], the optimization of energy usage for the purpose of local supply and demand matching of all commodities and considering flexibilities of all appliances are studied in this paper. The main contributions are as follows:

- We build a general system model of MC-SES and a mathematical model for the energy management in this MC-SES, which is suitable for different optimization objectives. The system model concerns various types of flexible appliances based on the concepts of the FPAI, as well as different running modes and nonlinear co-efficiency for CHP and electric heaters.
- We propose a greedy based algorithm for energy management, which tremendously reduced the computational complexity compared to global optimization of the management objective.
- Simulations of the MC-SES have been carried out, where the energy management problem is solved with global optimization, the greedy allocation and directly allocation.

The rest of the paper is organized as follows. The literature review and relevant concepts of FPAI are briefly introduced in Section 2. Then, based on the system model built in Section 3, the mathematical model of the multi-commodity energy management problem is formulated in Section 4. To solve this problem, a greedy algorithm is proposed and compared with global optimization methods in Section 5. The performance of the greedy algorithm compared to optimal solutions and direct allocations is further verified in Section 6 with simulation results. Finally, we draw the conclusions in Section 7.

2. Related work of energy management

In this section, we first present the literature work in MC-SES and the research gap. Then, the most relevant concepts defined in the FPAI [23] are introduced, which are prerequisite to understand the models and algorithms later in this paper.

2.1. Literature review

Flexible energy demands are the demands that can be adjusted and rescheduled within certain constraints, which are believed to take an important part of the total energy demands [5]. Energy management in smart grid adopts mechanisms and strategies that schedule and manage the flexible demands to achieve certain goals, e.g., energy efficiency, general grid operation supports, renewable energy management and environmental impacts eliminations [5,26–28]. DSM is a method to flexibly manage the energy usage at the demand side to achieve these goals [8,9]. DR is a special type of DSM schemes to make use of the electricity market and let the demand sides either voluntarily or forced to react on the electricity price to achieve the above mentioned goals [10–12]. Sometimes, researchers also use the terms DSM and DR interchangeably for example in [29]. Originally, DSM and DR programs only study the electricity energy and power gird [8,30–32], however, because of the popularity of micro-CHP and HP, more and more studies can be found that jointly consider thermal and electricity energy in MC-SES [5,9,28,33].

However, energy management in MC-SES is still challenged in different aspects. First of all, flexibility offered by appliances can exhibit several types, such as postponing or advancing a certain consumption and buffering or storing energy. The MC-SES must be able to deal with all of those appliances, which mostly results in complex problems. Therefore, energy management for MC-SES has often been subject to research. For example, the research presented in [17] focusses on various flexible electrical loads in combination with a home heating installation, incorporating extensive models of home and heater properties. However, these models lack the possibility to supply thermal energy from different sources and exchange this thermal energy among appliances using a district heating system. In [18] both an electrical and district heating system are included in a multi-commodity DSM system. The work is based on a market scheduling approach performing instantaneous local supply and demand matching for both electrical and thermal energy. This way, the system cannot take into account the time horizon flexibility of appliances, which highly limits the applicability for different optimization purposes. More works regarding multi-commodity management can be found in literature. For example, in [19], the combination of electricity and heat are analyzed. The considered scope is also within district heating system which is not applicable in every country. A smaller scope of multi-commodity network is more economic and flexible in deployment.

In some other previous works, only scenarios with specific thermal devices and demands are considered, which lead to the lack of a general framework for energy management in MC-SES. For example in [33], both thermal energy and electricity were studied to react on the day-ahead and balancing market to reduce the energy bills of users. However, only the thermal demands of space heating are considered in the proposed schemes in [33], which neglect the other types thermal demands (e.g., demotic hot water demands) and flexibilities. Another example is [9], in which only resistive hot water heaters are considered in the scenarios. However, CHP and HP are believed to be the future of thermal energy generators because of the high efficiency [34,35]. In [36], a dual tank solar-assisted heat pump (SAHP) system was studied to optimize the energy efficiency by adopting solar thermal collectors, thus, the algorithms in this paper is difficult to be used in other MC-SES scenarios. In [21,22,26,33], pricing and markets were involved to achieved multi-commodity DR. These works studied energy management from the grid operator side instead of the household side by assuming households are free to participate the energy market and react on the price. However, this assumption is not feasible yet in most countries. Note that there are many other research works in MC-SES, for example in the energy saving in agriculture [37], combined gas and heat supply in smart city [38] and energy network planning [39], however, these topics are out of the research scope of this paper, which will not be discussed further.

To overcome these challenges, an optimization algorithm has been proposed in our previous work [25], but the complexity of the energy management in multi-commodity SES was out of consideration. In this paper, we further extend from the previous work with an in depth assessment of the computational burden for finding an optimal solution. In order to solve the problem within the fast timing constraints for real-time scheduling, a greedy algorithm is proposed that can find a close to optimal solution with a significant deduction of the computational complexity compared to the global optimization method. This algorithm will be based on an