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Mixed-integer linear programming-based optimal configuration planning for energy hub: Starting from scratch

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HIGHLIGHTS

- A starts-from-scratch configuration planning model for community level MES.
- Jointly optimization on the energy generation, conversion and delivery.
- The nonlinear problem is transformed into an MILP model based on graph theory.
- Real-world case study for subsidiary administrative center of Beijing, China.

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ABSTRACT

The electric power, gas, and heat systems work on different but complementary time and space scales. Multiple energy systems (MES) yields an increase on the efficiency and flexibility of energy supply. The coupling between different forms of energy bring difficulties in the planning of the overall energy system. This paper proposes a novel optimal planning method for a community level MES that jointly determines the optimal generation, conversion and delivery of electricity, heat, cooling, and other services. First, configuration planning of a community level MES is introduced and defined using the energy hub (EH) concept. Then, the planning problem is presented with the objective of minimizing the sum of the investment and operating costs, with variables that represent the selection of energy converters or storage and their relationships. The model is then formulated as a mixed-integer linear programming (MILP) problem based on graph theory. The proposed model does not requires any pre-assumptions on the configurations of the EH so that it can plan the MES starting from scratch. Finally, an illustrative example is provided to describe the functioning of our proposed method. A numerical case study for the planning of a subsidiary administrative center in Beijing, China is presented to demonstrate the effectiveness and superiority of the proposed method.

1. Introduction

The integration of different energy systems yields an increase on the efficiency and flexibility of energy systems supply. Traditionally, different energy systems, such as electric power, gas, and heat systems, operate almost independently of each other. However, these systems are complementary. For example, electric power is suitable for long distance transmission, but requires real-time balancing, while heat can be easily and efficiently stored but should be locally balanced. To take advantage of the complementary characteristics of different energy systems, the concept of multiple energy systems (MES) promotes optimal interactions between each type over different time and spatial scales [1–3]. MES have been extensively recognized as an effective way to increase the efficiency of an entire energy system and provide more flexibility to accommodate renewable energy sources [4–6].

An MES consists of energy converters, energy storage devices, and an energy distribution networks. Converters transform energy into other forms to meet various energy demands [7]. For example, a combined heat and power (CHP) unit uses gas to produce electricity and heat; heat and electricity can be stored for use at a later time. Networks of pipes and wires transport different types of energy to different locations. Power lines, heat pipes, and gas pipes compose the networks. The operation of MES is constrained by the conversion characteristics of the energy converters (e.g. their efficiencies) and the characteristics of the interconnectors (e.g., power flow equations in electrical power systems, network flow in heat pipes) [8–10].

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Nomenclature

MES	multiple energy systems	$\boldsymbol{L}$	output energy of EH
EH	energy hub	$\boldsymbol{P}$	input energy of EH
CHP	combined heat and power	$\boldsymbol{C}$	coupling matrix
EB	electric boilers	P	total number of input ports
AB	auxiliary boiler	Q	total number of output ports
CCHP	combined cooling, heat, and power	$\boldsymbol{X}$	input-output port incidence matrix
CERG	compression electric refrigerator group	$\boldsymbol{H_g}$	energy conversion characteristics matrix
WARG	water absorption refrigerator group	$\boldsymbol{A_g}$	converter-branch incidence matrix
HP	heat pump	$\boldsymbol{Z_g}$	energy conversion characteristics matrix
TS	thermal storage	$\boldsymbol{V}$	set of all energy flows
		$\boldsymbol{W_n}$	output incidence vector
		$\boldsymbol{U_m}$	input incidence vector

Countries around the world have set aggressive goals in developing MES. The Department of Energy (DOE) in the United States has proposed an integrated energy system (IES) plan since 2001 [11]. Switzerland launched a research initiative on a "Vision of Future Energy Networks" in 2003 [12]. Denmark has tried to accommodate a high penetration of renewable energy by developing CHP and central heating [13]. In China, the government issued an action plan for the construction of an Energy Internet, where building MES is one of the key tasks [14]. There are many MES demonstration projects in planning or under construction. At the community level, for an MES covering a small area, energy transmission limits can be neglected and the energy conversion and storage can be modeled using the energy hub (EH) concept [15]. An EH models the coupling of different energy systems from an input–output perspective. Scholars around the world have conducted substantial studies on the operation, planning, and evaluation of MES using the EH concept. In this paper, we focus on the planning of an EH.

Joint planning of a MES takes advantage of the synergy of various energy types to improve the utilization of the assets and reduce the planning cost. The purpose of EH planning is to determine whether, when and where to build energy converters and storage devices and how they should be connected to each other [16]. EH models include houses [17], other buildings [18], and communities [19], and the energy converters and storage devices to be planned include CHP units, heat or electricity storage, electric boilers (EB), etc. [20]. Kienzle et al. quantified the value of investments in an EH through Monte Carlo simulation and optimal dispatch [21]. Geidl et al. proposed a nonlinear optimization model to determine their structure [22]. A topological optimization problem is formulated to obtain optimal connections of the converter, and a simple ad hoc solution is proposed to overcome the problem of infinite solutions in [23]. Shahmohammadi et al. put forward a comprehensive linearized model for optimal design of an EH considering reliability constraints [24].

Investigating the optimal size of energy converters and storage devices is another typical planning problem for an EH. Sheikhi et al. proposed a cost/benefit analysis approach to optimize energy converters based on reinforcement learning to determine the capacities of the CHP, auxiliary boiler (AB), absorption chiller, and transformer [25]. Bahrami et al. established an optimization model to find the optimal size and operation of a combined cooling, heat, and power (CCHP) and AB for buildings. A hospital is used as an example to verify the proposed method [26]. EH is used to model a hotel building in San Francisco and a residential building in [27,28], respectively, where the CHP capacity is optimized. Beyond planning for a single EH, Pazouki et al. proposed optimal CHP placement and sizing in a multiple energy network considering network reliability, power losses, and voltage profiles [29]. Salimi et al. formulated an optimal EH planning model in an interconnected natural gas and electricity system [30]. Zhang et al. expanded the concept of EH by determining appropriate investment candidates for generating units, transmission lines, natural gas furnaces and CHPs [31]. Qiu et al. provided a linear expansion model to minimize the overall capital and operating costs for coupled gas and power systems [32].

During the urbanization process in developing countries, undeveloped districts require multiple types of energy from the beginning, and thus rises the question of start-from-scratch MES planning, which means to jointly optimize what kinds of converters to choose, what their capacity should be, and how they should be connected. Although a substantial number of papers discuss the optimal planning of an EH, to the best of our knowledge, this is the first paper that discusses such optimal configuration planning of a community level MES which does not require strong pre-assumption. The method proposed in this paper addresses two challenges: (1) the configuration of the energy converters and storage devices is unknown, and it is difficult to integrate the configuration optimization into a conventional planning model; (2) existing optimal EH planning approaches involve mixed-integer nonlinear programming (MINLP), which are obviously difficult to solve.

In light of the above, the contributions of this paper are summarized as follows:

(1) A novel optimal configuration planning model for an EH that starts from scratch is originally proposed to jointly determine the energy generation, conversion and delivery of a community level MES.
(2) Graph theory and branch energy flow based EN modeling method is proposed to flexibly formulate the characteristics and topology of the energy converters and storages.
(3) The nonlinear problem is transformed into a mixed integer-linear programming (MILP) problem based on big M method. This results in tractable computations and is extendable to various purposes for EH planning.
(4) A real-world case of community level MES planning in a subsidiary administrative center of Beijing, China is carried out.

The organization of the rest of this paper is as follows: Section 2 defines the "planning from scratch" problem. Section 3 introduces the branch energy flow based EH modeling method. Section 4 describes in detail the mathematical formulation of the planning problem. Section 5, demonstrates the proposed method using an example. Section 6 uses a case study for an actual subsidiary administrative center in Beijing, China to demonstrate the effectiveness and superiority of the proposed method. Finally, conclusions are drawn and future work is described in Section 7.

2. Problem statement

Optimal EH configuration planning differs from the typical EH planning problem or power system planning problem in two ways: (1) Traditionally, part of the configuration of the EH and the types of energy converters have already been decided. In this study, there is no presumption about the configuration or the converters to be chosen for the EH. (2) Most of the existing literature only optimizes the capacity of the converters. In this paper, we optimize simultaneously the capacity