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Feasible region method based integrated heat and electricity dispatch considering building thermal inertia

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HIGHLIGHTS

- A feasible region method is proposed for formulation of new DHS models.
- The new models are similar to virtual power plant (VPP) concept.
- The flexibility of DHSs with consideration of building thermal inertia is exploited.
- It enables integrated heat and electricity dispatch in an electricity control center.
- Privacy, communication, dimension, and compatibility are considered.

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ABSTRACT

Integrated heat and electricity dispatch is crucial to exploit synergistic benefits from integrated energy systems. However, this requires information from both electricity systems and district heating systems (DHSs), which are managed by an electricity control center (ECC) and district heating control centers (DHCCs), respectively. For reasons pertaining to privacy, communication, dimension, and compatibility, it is not practical for DHCCs to send detailed models to the ECC. Therefore, a new feasible region method is proposed for formulation of new DHS models, which exploit the flexibility of DHSs with consideration of building thermal inertia. A greedy method is developed to solve the new modified feasible region models by calculating a series of linear programming problems efficiently. Then the new models are sent to the ECC to be used in central dispatch considering DHS operation constraints, i.e. integrated heat and electricity dispatch. The modified models are similar to conventional power plants and storages, and are thus compatible with current dispatch programs. Case studies verify the effectiveness of the method. Although some conservativeness exists, the total cost and wind energy curtailment are both decreased compared to conventional decoupled dispatch.

1. Introduction

In recent years, integrated energy systems (IESs), also named multi-energy systems or multi-vector energy systems, have developed rapidly in response to the challenges of energy efficiency improvement, CO_2 emission reduction and renewable energy integration [1–7]. In an IES, at least two energy systems, such as electricity, heating [8], cooling [9], gas [10], or transportation [11] system, are coordinated. Coordination leads to a number of synergistic benefits, such as lower investment and operational costs, higher renewable energy integration and a more reliable energy supply.

Heat and electricity coupling represents a typical IES. Central and district heating is ubiquitous in winter, especially in northern Europe and northern China, where combined heat and power (CHP) units play important roles [12,13]. For example, in Jilin province, northeastern China, over 70% of the heating load is supplied by CHP units. CHP units can produce heat and electricity simultaneously, coupling heating and electricity systems. Conventionally, the operation of CHP units is determined by heating loads and the flexibility to adjust electricity generation is lost. However, this dispatch framework has caused large wind energy curtailment. At off-peak hours in winter, electricity demands are quite low while heat loads are high. To meet heating demands, CHP units have to remain on and generate a certain amount of electricity, which occupies the wind energy generation fraction due to an inadequate downward spinning reserve. This leads to high wind energy curtailment. For example, 89% of the total wind power curtailment in 2013 in Jilin province was for this reason [14].

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Nomenclature

Indices and parameters

$\alpha, \beta, \gamma, \underline{E}_{S,k,p}, E_{S,k,q}$, $\mathbf{c}, \mathbf{v}_b, \mathbf{A}_{in}, \mathbf{A}_{amb}, \mathbf{A}_{rs}, \mathbf{c}_r, \mathbf{R}$	temporary variables, vectors or matrixes
η	heat to power ratio
k	*k*th time interval
i	*i*th building
C_p	specific heat of water (J/(kg K))
C_b	heat capacity of the building (J/°C)
KF	heat transfer coefficient of a building
M	number of buildings
$\mathbf{S}$	storage matrix
U_{Ab}	conductance between the indoor and ambient air of a building (W/°C)
$\overline{X}$	upper bound of variable X
$\underline{X}$	lower bound of variable X
$\mathbf{X}$	vector of variable X
Δt_k	duration of the *k*th time interval

Variables

m	mass flow rate of the source (kg/s)
m_b	mass flow rate via a building (kg/s)
s	sensitivity coefficient
$\mathbf{E}_S$	virtual storage energy (MW h)
P	electrical real power of a source (MW)
Q	heat power of a source (MW)
T_{amb}	ambient temperature (°C)
T_{in}	building inlet temperature (°C)
T_b	building indoor temperature (°C)
$T_{b,0}$	initial temperatures of a building, i.e. temperature before 1st time interval

On the other hand, heating systems have significant flexibility to adjust their heat or electricity generation through thermal inertia or thermal storage. Many studies have shown the effectiveness of district or central heating systems in improving renewable energy integration and energy economy. For example, Kiviluoma et al. investigated the benefits of combining electric heat boilers, heat pumps, CHP plants and heat storages in a district heating network to facilitate the integration of variable power [15]. Nuytten et al. proposed a model to evaluate the theoretical maximum flexibility of a CHP system and studied the impacts of different thermal energy storages [16]. Meibom et al. analyzed the economic value of electrical heat boilers and heat pumps as wind power integration measures [17]. Teng et al. presented an advanced stochastic analytical framework to quantify the benefits of smart electric vehicles and heat pumps [11]. Specially, Kensby et al. studied the potential of residential buildings as thermal energy storage in district heating systems [18], and Brange et al. also evaluated the annual prosumer potential of buildings [19]. Impacts of optimization interval on home energy scheduling were studied in [20].

Some research had done combined modelling, analysis and assessment to utilize this flexibility provided by heating system [8,9,21,22]. Specially, this paper explores the integrated heat and electricity dispatch, which is crucial in operation stage. Dispatch is usually formulated as an optimization problem. Different models and algorithms are developed in theses research. Awad et al. explored the integrated optimal power flow for power and heat networks in a microgrid [23]. Wu et al. proposed an optimization model for a CHP microgrid containing renewable energy to improve the utilization rate of renewable energy and achieve maximum economic revenue [24]. Chen et al. explored the additional flexibility provided by electrical boilers and heat storage tanks, and proposed a centralized dispatch model [25]. Yang et al. proposed a method to use thermal energy storage, distributed electric heat pumps and building thermal inertia to follow wind power [26]. Jiang et al. used a group search optimizer to optimize the operation of a direct district water-heating system with a wind turbine generator [27]. Li et al. studied the CHP dispatch and unit commitment problems and utilized the pipeline energy storage of a district heating network to increase wind power utilization [28,29]. Li et al. investigated an optimal way to integrate the integrated electrical and heating systems to accommodate more intermittent renewable [30]. Yang et al. proposed a paradigm and operation model for regional multi-energy prosumers using energy hub models [31].

These works assumed that heat and electricity information is managed centrally by one control center; which is a practical assumption for a small microgrid managed by a single company. However, across a larger area, such as a city, there may be many small district heating systems (DHSs) in different districts, and only one electricity control center (ECC) managing the entire electricity system. DHSs are usually owned by different companies to those that own the electricity system. These companies can establish district heating control centers (DHCCs) to manage DHSs. A future dispatch framework is shown in Fig. 1. Information and models are exchanged between the ECC and DHCCs to achieve coordination. It is unreasonable for these DHCCs to send detailed raw information to the ECC because of privacy concerns and because this also requires additional communication. The burden on the ECC is also increased due to the large amounts of information and models arising from a large number of DHSs. In addition, new dispatch models and programs are needed, because the additional heating models are different from the conventional electricity model. Some distributed methods have been developed to cope with certain of these problems, such as Lagrangian relaxation method [32], approximate Newton directions method [33], Benders decomposition [34], alternate direction method of multipliers [35], and multi-agent genetic algorithms [36]. However, these methods still need repeating information exchanges between the ECC and DHCCs, and the ECC still requires additional algorithms to perform coordination.

A more reasonable method is that each DHCC manages its DHS by itself and sends a modified model to the ECC. The modified model is more condensed and privacy preserving, but still provides enough information for the ECC to complete integrated dispatch. It also should be compatible with the current dispatch program in the

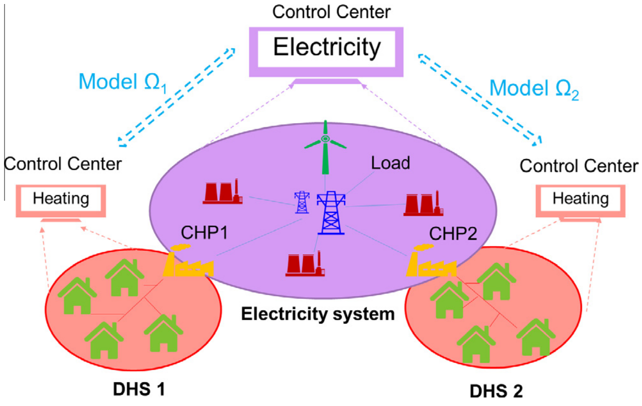

Fig. 1. Future dispatch framework.

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