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Automatic and linearized modeling of energy hub and its flexibility analysis

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HIGHLIGHTS

- A linearized EH coupling relationship modeling method is formulated.
- It facilitates the automatic modeling of arbitrary configurations of MES.
- The flexibility of an EH that can meet the demands is systemically analyzed.
- An efficient linear programing based interval optimization model is proposed.

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ABSTRACT

The integration of multiple energy systems (MES) provides opportunities to explore the flexibility to accommodate more renewable energy. The concept and methodology of energy hub (EH) enable the standardized modeling of district MES. However, current EH formulations introduce nonlinearities into the modeling and present challenges to analysis and optimization. This paper proposes an automatic and linearized modeling method to formulate energy conversion in EHs, which simplifies the optimization of EH operations. On this basis, the flexibility of an EH is analyzed and quantitatively evaluated based on the ranks of the coupling matrices of the EH and its feasible operational region. Finally, an application of the linearized model on the interval optimization model is illustrated to show how it can suppress uncertainties and fluctuations in distributed renewable energy. A case study is used to demonstrate the effectiveness of the proposed model and the rationality of the flexibility analysis by comparing two EHs with different flexibilities.

Overlines ($\bar{\ }$) above variables denote extreme cases with upper bounds of renewable energy forecasts, while underlines ($\underline{\ }$) denote extreme case with lower bounds of renewable energy forecasts, and those with hats ($\hat{\ }$) denote cases with expected values of renewable energy forecasts.

1. Introduction

Energy systems are undergoing a series of significant revolutions [1,2]: (1) the integration of high penetrations of renewable energy introduces large pressures on energy balancing; (2) the environmental and economic concerns increase the need for higher energy utilization efficiencies; and (3) information communication technologies enable smarter control and operation. Multiple energy systems (MES) are therefore becoming increasingly relevant in terms of energy production, conversion, delivery and utilization [3,4].

Many studies have been conducted to optimize the operation and planning of MES. For example, a unified steady-state power flow considering electrical, natural gas, and district heating networks is proposed in [5], and methods for calculating optimal power flow in MES are illustrated in [6,7]. An interval optimization-based coordinated operating strategy for a gas-electricity integrated energy system (IES) is proposed in [8]. A corrective receding horizon scheduling method for flexible distributed multi-energy microgrids is proposed in [9]. A bi-level optimal dispatch model for integrated natural gas and electricity systems is proposed in [10]. A combined gas and electricity networks expansion model is proposed in [11]. The results show that demand-side response plays a crucial role in improving gas supply security. Multi-agent systems were used for MES optimal operation in [12], where results show that balancing costs can reduce to 50%.

The integration of MES can increase the flexibility of energy systems to accommodate more renewable energy [13,14]. The large-scale storage of heat and gas systems, the freedom to switch between different forms of energy, and the flexible conversions of energy forms provide additional flexibility to electric power systems [15]. Such flexibility can compensate for the uncertainty and variability of renewable energies such as wind power and solar energy. The overall energy system needs

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Notation

Acronyms

AB	auxiliary boiler
CERG	compression electric refrigerator group
CHP	combined heat and power
EES	electrical energy storage
EH	energy hub
ES	energy-storage component
PV	photovoltaic module
RE	renewable energy
WARG	water absorption refrigerator group

Subscripts and superscripts

c	charge of storage components
d	discharge of storage components
i	index of energy-storage components from 1 to N_{ES}
t	index of time period from 1 to T
D	energy demand
I	inlet of energy hub
O	outlet of energy hub
S	variable related to storage component
Inte	intermediate variable of energy hub
Dis	augmented variable of energy hub
max	maximum value of variable
min	minimum value of variable
total	joint outlet of wind farm and energy hub

Parameters

α	freedom degree of energy hub operation
β	degrees of freedom of uncertainty accommodating flexibility
η	energy conversion efficiency
γ	self-discharge rate of energy-storage component
λ	lagrange multiplier
ρ	energy price
δ	cost corresponds to the deviations of energy demand between day ahead and real time
Δ	deviations of inlet energy flow of energy hub between day ahead and real time
N_{Inte}	number of intermediate variables
N_{Dis}	number of augmented variables
N_{ES}	number of energy-storage components
T	number of time intervals under consideration
F	energy flow of gas
Q	energy flow of heat
R	energy flow of cooling
W	energy flow of electricity
E	generalized energy flow (could be F, Q, R or W)
G	expected total inlet energy cost
$\mathbf{L}$	vector of outlet variables
$\mathbf{T}$	vector of intermediate variables
$\mathbf{P}$	vector of inlet variables
$\mathbf{V}$	vector of energy augmented variables
$\mathbf{C}$	coupling matrix of energy hub
$\mathbf{\Omega}$	operation region of energy hub
Γ, Π	range of load that an energy hub can supply

from fossil fuels would be reduced because of the accommodation of more clean energy [16]. The coordination of MES becomes an efficient solution to promote the integration of renewable energies because the flexibility provided by heat and gas storage or networks is much less costly than that of electric power systems such as batteries [17,18]. Some studies have studied using the coupling different forms of energy systems to accommodate the uncertainty and intermittency of renewable energy. Refs. [19,20] demonstrate that heat storage in the concentrated solar power can suppress the joint output uncertainty of solar power and wind power. A multi-agent genetic algorithm is proposed in [21] to cope with the uncertainty in wind power in a multiple energy carrier operations. Ref. [22] proposes a combined dispatch model for heat and power systems that considers the storage time delay and storage effect of heat networks and shows that the storage and slow dynamics of heat networks can accommodate wind energy more efficiently. Ref. [23] analyzes the benefits of introducing heat pumps and electric boilers into wind power integration. In [24], the flexibility of a heat and electricity combined microgrid is analyzed based on deterministic simulation and model predictive control. The way that a cold and heat system improve the flexibility of a hybrid system and the developments in different countries are introduced in [25]. A unified operation and planning optimization method for distributed MES is proposed in [26] to assess flexibility in both the operation and investment stages, subject to long-term uncertainties.

In addition to the substantial amount of research that has focused on the optimal operation and planning of MES, several papers have focused on modeling MES. In an analysis of MES, the concept of an energy hub (EH) is proposed to model a district MES [27]. The basic idea of an EH is to model the conversions of different energy forms as a multi-input multi-output energy conversion component. A coupling matrix is used to quantify the relationships among conversions between inlet and outlet ports. Currently, there are some preliminary studies on modeling MES using EHs. An automatic construction procedure for the coupling matrix of an EH is proposed in [28], a block schematic diagram method used to model a particular EH in Bilbao is shown in [29], and a decoupling method of the coupling matrix of an EH is provided in [30]. These studies provide inspiration to improve the basic model of EHs. Several studies on MES have been conducted using the theory of an EH. For example, a modeling method for plug-in hybrid electric vehicles based on the concept of an EH is given in [31]. An automatic demand side management methodology in EHs is analyzed in [32]. The demand response potential of MES with the participation of an EH is studied in [33,34].

The current model of EHs introduces nonlinearity into the modeling and presents challenges to analysis and optimization. In the basic EH model proposed in [19], dispatch factors are introduced in the coupling matrix presenting the split of energy flow when one branch is connected to several different parallel branches. Dispatch factors allow for flexible dispatches of energy flows within an EH to improve its operating performance. Therefore, dispatch factors need to be regarded as decision variables in operational and planning optimization models of EHs. As a result, coupling matrices usually contain dispatch factors or products of multiple dispatch factors. The EH model, which contains the coupling matrix term multiplied by the inlet energy flows, becomes highly nonlinear because the inlet energy flows are also decision variables. The operational and planning optimization of EHs faces numerical calculation issues due to the terms containing products of multiple decision variables. A concise ASCII based format for describing a general EH network is proposed in [35] to enable the optimization process to be implemented automatically by computer. By dividing an EH into different blocks to describe energy inputs, storage, conversions, and outputs, a linearized EH modeling method is proposed in [36]. A similar framework is also proposed in [37] for the optimization of a city level MES. The nonlinearity caused by the efficiency variance of energy convertors is linearized using a pricewise approximation method. However, the proposed method can only handle EHs with a specific