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Analyzing and validating the economic efficiency of managing a cluster of energy hubs in multi-carrier energy systems

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HIGHLIGHTS

- Three organization schemes are compared and aggregation is the most efficient.
- Sharing scheme can achieve near optimal efficiency without a central organizer.
- Concrete bilevel models for energy hub management in multi-energy system.
- An approximated mixed-integer linear program for computing the market equilibrium.

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ABSTRACT

The interdependency across natural gas, power and heating systems is increasingly tightened due to the wide development of cogeneration plants and electrified heating facilities. Multi-energy integration is a prevalent trend and the energy hub, which acts as an intermediary agent between providers and consumers, is expected to play a central role in allocating energy resources more efficiently. However, uncertainties originating from multiple kinds of energy demands challenge the operation of energy hubs and may compromise system efficiency. Energy trading and sharing among individual hubs offer a unique opportunity to increase system flexibility and reduce the cost under demand uncertainty. In this paper, three quintessential schemes for organizing a cluster of energy hubs at demand side, i.e., individual, sharing market, and aggregation, are studied under a stochastic framework with probabilistic load forecasts. First, we perform theoretical analysis and compare their economic efficiencies from a maximum-utility (or minimum-cost) perspective. Utility curves of respective schemes are given, and several important phenomena are revealed from the economic analysis. Then we discuss the concrete decision-making models of energy hubs under the three schemes, taking into account the change of electricity price in response to the total demand, which give rise to bilevel optimization problems and are technically transformed into mixed-integer linear programs. Finally, we conduct numerical experiments, which validate the theoretical outcomes, and reveal that the sharing scheme can achieve nearly optimal efficiency without a central organizer, and hence appears to be a promising direction for future multi-energy systems.

1. Introduction

Due to the synergy among different energy carriers [1], traditionally independently operated energy infrastructures such as the power grid, heating system, and natural gas system are now becoming increasingly interdependent because of the proliferation of co-generation plants, energy conversion devices, and energy storage units. Gas-fired combined heat and power (CHP) units have been proved to be more efficient compared with the separate production (an illustrative example can be found in [2]). The state-of-art air-source/ground-source heat pumps have a coefficient-of-performance (COP) up to 3–5 [3], which means that 3–5 times thermal energy can be extracted by consuming merely one unit amount of electricity. Although electric boilers have relative lower electricity-heat efficiency, they are very cheap to deploy and can absorb excessive renewable generation which is otherwise curtailed. In Europe, nearly 11% of its electricity was generated via cogeneration [4] while Denmark, the Netherlands and Finland are the world's most intensive cogeneration economies [5]. In Germany, over

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Nomenclature

Indices and sets

i	index of energy hubs
t	index of time periods
ω	index of scenarios
j	index of power generators
n	index of buses in power system

Parameter

N_E	the number of energy hubs
η_{eh}	efficiency of electricity to heat conversion
η_{gh}	efficiency of gas to heat conversion
η_{ge}	efficiency of gas to electricity conversion
λ_t^{ec}, λ_e	electricity price in the day-ahead market
λ_t^{gc}, λ_g	natural gas price in the day-ahead market
$\lambda_{t,\omega}^{M}$, λ_M	gas-to-power price in the sharing market
r_{mn}, x_{mn}	resistance/reactance of line mn
$\underline{v}_n$, $\overline{v}_n$	bounds of voltage magnitude square at bus n
$\underline{P}_j$, $\overline{P}_j$	bounds of active output of unit j
$\underline{Q}_j$, $\overline{Q}_j$	bounds of reactive output of unit j
$\bar{l}_{mn}$	square current capacity of line mn
p_n^l, q_n^l	active/reactive electricity demand at bus n
c_j	cost of generation unit j
π, π_ω	probability of each scenario
$\bar{I}$	budget of the energy hub
d_e, $\tilde{l}_{it,\omega}^{e}$	real-time power demand
d_h, $\tilde{l}_{it,\omega}^{h}$	real-time heat demand
E_m, H_m	the capacity of power/heat storage unit
$R_{pm}^{\pm}$, $R_{hm}^{\pm}$	maximum charge/discharge rate of storage unit
M	a large enough constant
(p_s, λ_s)	breakpoints in piecewise linear technique

Decision variables

θ	the expenditure of power
ρ_{it}	proportion of power converted into heat
$p_{it}^{e,in}$, $p_{it}^{g,in}$	input electricity/gas of the energy hub
$p_{it}^{e,out}$, $p_{it}^{h,out}$	output electricity/heat of the energy hub
p_{it}^{dis}, p_{it}^{ch}	discharge/charge rate of power storage unit
h_{it}^{dis}, h_{it}^{ch}	discharge/charge rate of heat storage unit
$\lambda_{t,\omega}^{er}$, $\lambda_{t,\omega}^{hr}$	price of electricity/heat in the real-time market
u_{it}, s_{it}	binary variables indicate the status of storages
E_t, H_t	energy amount of power storage/heat storage
p_{it}^{e0}, p_{it}^{g0}	contracted power/gas in day-ahead market
$\delta_{it,\omega}^{e+}$, $\delta_{it,\omega}^{h+}$	power/heat bought from the real-time market
$\delta_{it,\omega}^{e-}$, $\delta_{it,\omega}^{h-}$	power/heat sold to the real-time market
$p_{it,\omega}^{ex}$	energy exchange in the sharing market
p_j, q_j	the active/reactive output of power generator j
l_{mn}	square of the current in line mn
v_n	square of voltage magnitude at bus n
P_{mn}	active power flow in line mn
Q_{mn}	reactive power flow in line mn
λ_n	dual variable of the power balancing condition
α_s	continuous weight variables used in piecewise linear technique
β_s	binary variables used in piecewise linear technique
γ_s	auxiliary variables used in objective function linearization

50% of the nation's total electricity demand could be provided by cogeneration and it aims to double the share of cogeneration by 2020 [6]. In the UK, there has been a trend towards "multi-utility" bundling [7], increasing the coupling of multiple energy markets. CHP is already an important resource for the United State and constitutes 8% of generation capacity [8]. In this regard, the interdependence across multiple energy infrastructures will become more prevalent, especially in the countries/regions with long cold winter, creating strong interdependency in energy flow and market behavior [9].

Coordinated operation of multi-carrier energy systems has become a hot topic in recent years. The flexibility of combined heat and power system with thermal storage was evaluated based on a generic model in [10]. The energy flow of combined cooling heating and power system was analyzed under electrical demand management mode and thermal demand management mode respectively in [11]. The efficiency of separate operation and combined operation of heat and power production were compared in [12]. In many researches mentioned above, an implicit assumption is that a central operator has the authority to control components in all related systems. However, in current practice, different energy systems are usually owned or governed by individual entities, which may be unwilling to accept compulsory dispatch orders. In this regard, energy markets turn out to play an important role in allocating resources in a fairer way, since individual market participants can make decisions regarding their own purposes. The modeling and strategic planning methods of sustainable interdependent networks were presented in [13], where typical application examples can also be found.

The power market has been studied for decades. One classic organization is the pool-based market with the locational marginal price (LMP) scheme [14]. Traditional power market appears at the transmission level, and the market clearing comes down to a direct-current (DC) optimal power flow (OPF) problem [15]. Smart grid technologies allow the similar paradigm to be implemented in distribution systems. However, because the resistance to reactance ratio (r/X) of distribution lines is higher than that in transmission grids, the alternating current (AC) OPF model is used to clear the distribution market [16]. The gas market is much less competitive and flexible than the electricity market. In the gas spot market, the price tends to be proportional to the gas demand and usually remains unchanged throughout a day [17]. To study the strategic interactions among multiple stakeholders in the gas market, a generalized Nash-Cournot game model was proposed in [18], and complementarity programming models were developed in [19] which were applied in South Stream [20]. As we restrict our attentions on the intra-day transaction, the gas price is assumed to be fixed as in [21].

With the increasingly tightened coupling of energy systems with multiple carriers, the advent of integrated energy markets will greatly promote energy transaction and sharing among different physical systems. Along this line of research, the market power of natural gas producers on the power market was investigated in [22]. A multi-lateral trading model for the gas-heat-power coupled system was proposed in [23] and the market behaviors of different energy systems were considered. In [24], a strategic offering model for the gas-power system was presented. The gas market is cleared in a similar way as the power market. All the studies above consider the real-time market without uncertainty. However, in the day-ahead market, the uncertain factors such as load forecast errors can no longer be neglected and may affect the real-time decisions.

In power market analysis, the impacts of load and price uncertainties have been investigated. Because of the competition and strategic behaviors of individual market participants, incorporating uncertainty in a market equilibrium model is much more difficult than doing so in a centralized dispatch problem. For the supply-side power market, a robust Cournot-Bertrand model was proposed in [25] to mimic risk-averse bidding strategies of generation companies in a congested power grid. Ref. [26] proposed a day-ahead decentralized