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Bi-level optimization model for integrated energy system considering the thermal comfort of heat customers

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HIGHLIGHTS

- The thermal inertia of buildings and the economic benefits of users are considered.
- Meeting the thermal comfort demands by utilizing the acceptable temperature range.
- Integrating the lower-level problem as additional complementary constraints.
- The impact of some auxiliary equipment on wind power consumption is investigated.
- The influence of the gas tank characteristics on gas generation cost is studied.

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ABSTRACT

Significant growth in gas-fired combined heat and power units worldwide has enhanced the degree of interdependency between power, natural gas and district heating systems. This study establishes a bi-level optimization model for integrated energy systems that handles the interaction between centralized energy generation and the heating costs of end users in winter. The upper level of the model is designed to maximize the total benefit of the integrated energy system, and the lower level is designed to minimize the heating bills of residents. The lower level considers the thermal inertia of the building and the thermal comfort of the inhabitants. The indoor temperature demand is converted to a heat demand within a feasible interval. The nonlinear bi-level model is transformed into a mixed-integer linear programming formulation using the Karush-Kuhn–Tucker optimality condition. The optimal results of the traditional and proposed models are compared in case studies. The impacts of three representative auxiliary equipments (power to gas, electric boiler and gas tank) on wind power integration or gas generation cost are also investigated.

1. Introduction

At present, the efficient operation of energy resources poses a major global challenge [1]. The energy flows through different transmission networks such as electricity, natural gas and local district heating system are mostly planned and managed independently of each other [2]. However, the increase in the utilization of gas-fired and other distributed generation systems [3], especially co- and tri-generation, has raised energy-efficiency concerns, incentivizing the coordination of various energy systems to enhance energy services [4]. For instance, gas-fired combined heat and power (CHP) plants simultaneously produce electricity and heat [5]. Hence, the natural gas system is expected to be sufficiently flexible to ensure gas supplies to gas-fired CHP plants. With the popularization of the electrification of heating (such as electric heat pumps [6] and electric boilers (EBs) [7]), the electricity demand is increasingly affected by heating requirements. Integrated energy systems (IESs) offer a creative solution for future energy networks, but require the combined modeling and analysis of multi-energy systems.

One type of IES is the integrated power and natural gas system. Ref. [8] introduces the concept of distributed stack nodes to overcome the shortcomings of adjusting the active power balance by a single as-fired unit. Ref. [9] presents a mathematical formulation of a power-to-gas (P2G) facility that reduces CO_2 emissions and improves wind utilization. A steady-state analysis of an integrated natural gas and power system is presented in [10]. In [11], the authors optimized an integrated power and natural gas system by considering the gas

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Nomenclature

Indices and sets

Γ	set of indices of scheduling periods
GT	set of indices of gas turbine CHP units
$\mathbf{GC}(m)$	set of nodes connected to node m
$\mathbf{GC}(m)$	set of nodes connected to node m
$\mathbf{I}^{\mathrm{Line}}$	set of indices of transmission lines
$\mathbf{I}^{\mathrm{Load}}$	set of indices of electrical load buses
$\mathbf{I}^{\mathrm{bus}}$	set of indices of electric buses
NGF	set of indices of natural gas fields
NGP	set of indices of P2G plants
NGT	set of indices of natural gas tanks
$\mathbf{NGL}^{\mathrm{G}}$	set of gas nodes connected to natural gas turbine CHP units
$\mathbf{NGL}^{\mathrm{L}}$	set of gas nodes connected to residential loads
ST	set of indices of coal-fired steam turbines
$\mathbf{S}_n^{\mathrm{ST}}$	set of indices of coal-fired steam turbines connected to bus n
$\mathbf{S}_n^{\mathrm{GT}}$	set of indices of gas turbine CHP unit connected to bus n
$\mathbf{S}_n^{\mathrm{WP}}$	set of indices of wind turbines connected to bus n
$\mathbf{SC}(m)$	set of gas storage tanks connected to node m
WP	set of indices of wind farms

Input parameters

$a_i\ b_i\ c_i$	cost coefficients of coal-fired steam turbines
$a_{0,i}\ \ a_{5,t}$	cost coefficients of gas turbine CHP units
$\alpha_i\beta_i\gamma_i$	gas consumption coefficients of unit i
c_m	specific heat ratio of natural gas
C_E	equivalent heat capacity of buildings
$Cost_{s,t}^G$	gas generation cost of gas field s during period t
$\bar{C}\mathrm{S}_s/D\bar{C}\mathrm{S}_s$	maximum charging/discharging rate of gas tank s
$C_i^{\mathrm{ST}}(\cdot)$	generation cost function of coal-fired steam turbines
$C_i^{\mathrm{GT}}(\cdot)$	generation cost function of gas turbine CHP units
C_i^1–C_i^4	ratios of electric power to heat supply under different operation modes of CHP unit i
F_l	transmission capacity limit of line l
$G_{s,min}^{GF}/G_{s,max}^{GF}$	minimum/maximum gas generation rate of gas field s
$\underline{G}S_s/\bar{G}S_s$	minimum/maximum gas storage of gas tank s
$\bar{h}_i$	maximum heat output of CHP unit i
LHV	lower heating value of natural gas
$\bar{p}_{i,t}^w$	maximum power output of wind farm i during period t
$\underline{p}_i/\bar{p}_i$	minimum/maximum power output of generation unit i
$price_t^P$	power price during period t
$price_t^H$	heat price during period t
$profit_{s,t}^G$	sales profit of natural gas from gas field s during period t
$PL_{n,t}$	electric load at bus n during period t
$rup_i/rdown_i$	upward/downward ramping capacity of unit i
R	equivalent thermal resistance of buildings
SR^{up}/SR^{down}	system-wide upward/downward spinning

dynamics. The work described in [12] showed that large-scale gas storage is attractive to energy generation operators for its ability to manage excess base loads. In the event of natural gas pipeline outages, gas-fired generators without dual fuel capabilities could constrain the power system and eventually lead to power transmission congestion [13]. An interruption or pressure loss in natural gas pipelines may lead to generator losses or restrict the amount of fuel delivered to gas-fired generators. It is necessary to consider the natural gas transmission constraints when calculating security-constrained unit commitment [14]. Ref. [15] proposes a robust scheduling model for a wind-integrated energy system that takes into account gas pipeline and power transmission N-1 contingencies. An iterative methodology that uses linear sensitivity factors to solve the optimal flow is proposed in [16]. It allows system operators not only to perform security analysis but also to adjust the state variables in advance, so that N-1 contingences do not result in violations.

Another representative case of the IES is the integrated electricity and district heating systems. In the Jilin province of China, over 70% of the heat load is supplied by centralized CHP units. Nonetheless, the available wind power has been curtailed by more than 20% annually in recent years [17], primarily because the downward reserve of thermal generation units is inadequate [18]. Hence, improving the operational flexibility of CHP units would significantly benefit the use of wind energy. Heat pumps [19], electric boilers [20], and heat storage tanks [21] can facilitate the integration of wind power into CHP systems. Therefore, CHP systems need improved strategies for optimal sizing. The power source sizing strategy proposed in [22] takes into account the characteristics of distributed generation and energy storage. The authors of [23] take an analytical approach to find the optimal operation of fuel cells for home energy systems. For short-term optimal operation, [24] presents a detailed optimization model of the combined cooling, heat and power energy system. Some production details, including fuel switching for boilers and supplementary firing for gas turbines, are considered in [25]. Energy prices and load uncertainty are characterized through a stochastic programming formulation in [26]. Long-term planning for CHP systems involves a large number of decision variables. Ref. [27] presents novel mixed integer linear program methodologies that allow consideration of a year-long time horizon with hourly resolution while significantly reducing the complexity of the optimization problem. By studying the temperature dynamics and the thermal storage capacity of buildings, the authors of [28] devised a scheme that manages the dispatch of wind power through heating systems. However, they focused on the distribution network of the central heating system, because their proposed node network model was more suitable for small-scale than large-scale networks.

To summarize, various technologies have improved the design and implementations of heating systems integrated with electricity and natural gas systems. In this outlook, different energy systems interact with each other at various levels (for instance, within-district, citywide, and country-scale) [29]. Micro-grids [30], smart distribution networks [31] and smart energy hubs [32] have become mainstream technologies for the optimal management of multi-energy systems at the district level. In micro-grids, new technologies, such as fuel cells and microturbines, generate far fewer exhaust emissions of NO_x and CO_2 than traditional technologies employed at centralized power plants. Energy hubs comprise three basic elements: direct connections, converters, and storage devices. The energy hub provides an interface between energy participants. From the system viewpoint, an energy hub combines the input, output, conversion, and storage of multiple energy systems into a functional unit. However, from a spatial perspective, most studies focus on the district level.

Bi-level programming can effectively optimize the allocation of different energies [33]. In previous works, bi-level programming was applied to optimize the operation of power systems [34]. The authors of [35] propose a security-constrained bi-level economic dispatch model for power systems integrated with large-scale natural gas systems. Their model considers the wind power and the P2G process. By suppressing the volatility of the renewable energy in combined power and natural gas systems, P2G reduces the waste of wind sources and displaces carbon emissions, which is beneficial for long-term operation [36]. In