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A multi-lateral trading model for coupled gas-heat-power energy networks

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HIGHLIGHTS

- Optimal energy flows in the gas, heat, and power systems are modeled in detail.
- A multi-lateral trading model for the coupled energy markets is proposed.
- A two-phase algorithm for computing the market equilibrium.
- Case studies demonstrate that market competition pilots reasonable energy prices.

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ABSTRACT

The proliferation of cogeneration technology and the need for more resilient energy utilization inspire the emerging trend of integration of multi-resource energy systems, in which natural gas, heat, and electricity are produced, delivered, converted, and distributed more efficiently and flexibly. The increasing interactions and interdependencies across heterogenous physical networks impose remarkable challenges on the operation and market organization. This paper envisions the market trading scheme in the network-coupled natural gas system, district heating system, and power system. Based on the physical energy flow models of each system and their interdependency, a multi-lateral trading gas-heat-power (MLT-GHP) model is suggested, and a mixed-integer linear programming based two-phase algorithm is developed to find the market equilibrium. Case studies on two testing systems demonstrate the effectiveness of the proposed model and method, showing that the multi-lateral trading essentially results in market competition that orientates reasonable energy prices. Some prospects for future researches are also summarized.

1. Introduction

Nowadays, the interdependency among heterogenous energy systems such as the natural gas system, district heating system, and power system is becoming more and more prominent, owing to the proliferation of co-generation plants, e.g., gas-fired power generators, power-to-gas (P2G) facilities, and combined heat and power (CHP) units. While providing additional flexibility to energy production, these facilities create strong interdependency across multiple physical networks in energy flow and market organization layers as well [1–3]. In this regard, the integrated investigation of energy systems including multiple energy carriers and networks has become a hot topic.

Recently, a number of researches have been focused on the co-optimization of integrated energy systems in different timescales, including unit commitment [4,5], economic dispatch [6–8], expansion planning [9–11] and etc. Partly because of the complexity of energy flow models, most existing studies consider the coordination of two systems. For gas and power system co-optimization, a heated topic is the analysis of gas-power network's flexibility in accommodating renewable energy, such as wind power. Sahin et al. [12] proposes an algorithm to coordinate intermittent wind generation, gas units and hydro units to maximize the generating companies' payoffs. Forecast market price is used here to estimate the risks. Alabdulwahab et al. [8] and Guandalini et al. [13] studies the coordination of interdependent natural gas and electricity infrastructures for firming wind uncertainty and P2G is included in [7]. Gil et al. [14] presents two methodologies for joining the gas and electricity markets, taking into account the different interests of individual systems. For heat and power system

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Nomenclature

Indices and sets

t	index of time period
l	index of lines of the power grid
i	index of generation units
q	index of electrical demand
v	index of nodes in the district heating network
u	index of heat pumps
k	index of heat boilers
ς	index of inlet nodes in heating network
S	index of supply lines in heating network
R	index of return lines in heating network
y	index of nodes in the gas network
j	index of gas wells
w	index of gas loads
G	set of gas-fired units
A	set of gas pipelines in the gas network
M_l	set of nodes with heating demands in the heating network
M_p	set of nodes with heat pumps or heat boiler in the heating network
M_m	set of nodes with several inlets in the heating demands
S_v	set of inlet nodes of node v

Parameter

T	time period with each period equals to one hour
CG_j	cost for gas well
$S_j^{\min}$, $S_j^{\max}$	minimal/maximal gas output
$\pi_y^{\min}$, $\pi_y^{\max}$	minimal/maximal gas pressure
$G_k^{\min}$, $G_k^{\max}$	minimal/maximal gas purchased by heat system
l_{wt}	gas load in period t
$C_{y_1y_2}$	Weymouth equation coefficient
b_c	binary variable to indicate if compressor is on
α	compression factor of the compressor
T_a	ambient temperature
λ_0	heat transfer coefficient of a pipe per unit length
L_0	heat pipe length
c_p	specific heat of water at constant pressure
m	mass flow rate
R_i^+, R_i^-	ramp-up/down limit for thermal generator
$P_u^{\min}$, $P_u^{\max}$	minimal/maximal electricity purchased by heat system
$P_i^{\min}$, $P_i^{\max}$	minimal/maximal output of generator i if it is on
p_{qt}	load demand of power system
π_l	line flow distribution factor for transmission line l
F_l	transmission capacity on transmission line l
d_i	electricity output cost for generator i
η_{eh}, η_{gh}, η_{gei}	energy transfer efficiency from electricity to heat, from gas to heat and from gas to electricity, respectively

Decision variable

cge_i	gas price for gas-fired power units
g_{it}	gas sold to power generation unit i in period t
cgh	gas price for heat boilers
h_{kt}	gas sold to heat boiler k in period t
ceh_{ut}	electricity price for heat pumps
p_{ut}	electricity sold to heat pump u in period t
s_{jt}	output of gas well j in period t
$f_{y_1y_2,t}$	gas flow from node y_1 to node y_2 in period t
π_{yt}	gas pressure at node y in period t
$T_{\varsigma t}$	temperature of inlet lines
$T_{vS,t}$, $T_{vR,t}$	temperature of supply line and return line
p_{it}	electricity output of unit i in period t
p_{gt}	electricity bought by moto-compressor in period t

co-optimization, [15] investigates the impact of power-ramp constraints on the CHP units planning and a relaxed ramp-constraint is presented to develop a robust heuristic. Zhigang et al. [16] uses the strong coupling characteristic of electric power generation dispatch and heat supply of CHP units to accommodate variable wind, and [5] is its unit commitment counterpart. Rolfsman et al. [17] considers the economic benefit of short-term coordination between CHP and heat storage in the market environment.

Although two-network-coupled system has been studied well, researches on multi energy carrier is very limited. One common solution is the energy hub, which plays a role as an interface between consumers and transmission system [18]. A energy hub can be identified as a unit that provides the basic features like input and output, conversion and storage of different energy carriers and can be described as a multi-input multi-output black box via algebraic equations [19]. A steady state power flow model of gas-heat-power coupled network with energy hubs is studied in [2] and a general optimality condition is put forward. More general model is derived in [20] for optimal dispatch of multiple energy carriers. Chengcheng et al. [21] puts forward a state variable-based linear energy hub model to avoid the introduction of dispatch factor in conventional models. Mashayekh et al. [22] models the energy coupling directly and a mixed integer linear programming approach is proposed for multi-energy microgrid design aiming at minimizing the overall microgrid investment and costs. However, the above studies with energy hubs, assume that the whole network is managed by a central entity with a consolidated objective, and ignore the inherently self-regarding behaviors of individual subsystems. For example, the electricity, heat, and gas providers may seek for their best strategies individually in a competitive environment. To better understand the market behavior in the coupled energy systems, [23] studies the optimal pricing for electricity and natural gas system with CHP using particle swarm optimization method. Although the heat system is also considered there, it actually provides fixed demand only without active decision-making activities.

Among the energy pricing schemes in smart grid, a widely used one is the nodal price or locational marginal price (LMP) [24,25], which represents the marginal cost for supplying one additional unit of demand. LMP can be extracted from the dual variables associating with power balancing equations in an optimal power flow problem. Hu and Ralph [26] uses an equilibrium problem with equilibrium constraint (EPEC) structure to accommodate multiple providers competing in the upper level. But the transaction between the providers and consumers in the upper level has not been taken into account.

This paper develops a multi-lateral trading (MLT) scheme for the joint gas-heat-power (GHP) market. The market includes three bilateral trades: a gas trade between the gas network and gas-fired units in the power grid; an electricity trade between the power grid and heat pumps in the heating network; a gas trade between the gas network and heat boilers in the heating network. Main contributions of this paper are threefold: