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Security-constrained bi-level economic dispatch model for integrated natural gas and electricity systems considering wind power and power-to-gas process

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HIGHLIGHTS

- A bi-level dispatch model to minimize the total operation costs is proposed.
- Supply for both natural gas and electricity is dispatched economically and simultaneously.
- P2G is considered in short-term operation of the integrated energy systems.
- P2G may help wind power accommodation with reduced emission and gas consumption.

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ABSTRACT

Worldwide natural gas consumption has increased significantly, especially for power generation in electricity systems with the gas-to-power (G2P) process of natural gas fired units. Supply for both natural gas and electricity systems should be dispatched economically and simultaneously due to their firm interconnection. This paper proposes a security-constrained bi-level economic dispatch (ED) model for integrated natural gas and electricity systems considering wind power and power-to-gas (P2G) process. The upper level is formulated as an ED optimization model for electricity system, while the lower level is an optimal allocation problem for natural gas system. Natural gas system is modeled in detail. In addition, the security constraints and coupling constraints for the integrated energy systems are considered. The objective function is to minimize the total production cost of electricity and natural gas. The lower model is converted and added into the upper model as Karush-Kuhn-Tucher (KKT) optimality conditions, thus the bi-level optimization model is transformed into a mix-integer linear programming (MILP) formulation. Numerical case studies on the PJM-5bus system integrated with a seven-node gas system and IEEE 118-bus system integrated with a modified Belgian high-calorific gas system demonstrate the effectiveness of the proposed bi-level ED model.

1. Introduction

As one of the most important fossil fuels, the natural gas consumption in the world has increased significantly in the last decade, especially for the use in power generation. By 2030, the gas-fired generation is expected to increase by 230% [1,2]. At the same time, the number of natural gas fired generating unit (NGFGU) installations has grown dramatically, which results in the tight coupling between the electricity systems and the natural gas systems [3]. Compared with conventional coal plants, NGFGUs have higher economic efficiency, lower environmental emissions and faster response capabilities [4].

Gas-fired power plants provide a linkage between natural gas and power systems. Due to the interdependence between electric power and natural gas systems, the economy and reliability of the two energy sectors would be influenced by each other directly [5,6]. On one hand, the price of natural gas fluctuates, leading to the change of operating cost of NGFGUs [7], and thus affecting the economy of power system. On the other hand, the security regions of electric power systems and natural gas systems cannot

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Nomenclature

GSF_e	generation shift factor
t/T	time period
F_{nj}	pipeline flow
GSFgas/GSF	gas/generation shift factor
$\pi n/\pi j$	nodal pressure
c_i	bid of generating units
$P_{i,t}$	power output of generating units
$Limit_{gas,nj}/Limit_l$	pipeline/transmission line limits
$\eta_{i,sr}$	cost coefficient for spinning reserve
η_{G2P}	efficiency of NGFGU
$P_{wind,t}^{forecast}$	wind power forecasting output
D_t	electricity load
P_{imin}/P_{imax}	lower/upper limits of generation
R_d	reserve for wind power
R_{down}/R_{up}	spinning reserve requirement
$S_{m,\min}/S_{m,\max}$	lower/upper limits of gas supply
$\lambda/\omega_m^{\min}/\omega_m^{\max}/\mu_{nj,t}^{\min}/\mu_{nj,t}^{\max}$	dual variables
${v_{\mu,nj,t}}^{\min}/{v_{\mu,nj,t}}^{\max}/{v_{\omega,m,t}}^{\min}/{v_{\omega,m,t}}^{\max}$	auxiliary binary variables
m, n, j	natural gas system nodes
M/N	number of gas supply and generating units
C_{nj}	pipeline constant
NG	number of natural gas nodes
S_m/GL	natural gas supply/load
c_{wind}	bid of wind farm
$Price_{m,gas}$	gas price
$P_{wind,t}$	dispatched wind power output
π_{cw}	cost coefficient for wind curtailment
η_{P2G}	efficiency of P2G
$E_{P2G,t,gas}/S_{P2G,t,gas}$	energy/volume of natural gas from P2G
$D_{m,t}$	electricity load for P2G
$Ramp_i^u/Ramp_i^d$	ramping rate of generating unit
$\overline{S_{P2G,gas}}$	upper volume limits of gas from P2G
$GL_{P2G,t,gas}$	virtual natural gas load of P2G
$GL_{\min}/GL_{\max}$	lower/upper limits of gas load
$M_\omega^{\min}/M_\omega^{\max}$ $M_\mu^{\min}/M_\mu^{\max}$	large enough constants

be considered independently due to their inherent interdependency [2,8]. Therefore, the economic operation problem of integrated natural gas and electricity system should be analyzed simultaneously. The security constraints of both electricity and natural gas systems should be taken into account.

For the optimal operation of integrated natural gas and electricity systems, the studies on single- or multiple-period operational optimization are investigated in [3,4,7,8,13,14,15]. In the conventional optimal operation of electric power systems, the dispatch of NGFGUs along with other thermal sources such as coal, oil and nuclear does not consider the fuel supply constraints. However, with the growth of the natural gas market, the limit of the natural gas network with the increasing demand of NGFGUs becomes an issue that is not negligible [9]. In [10], the authors developed an algorithm to solve the problem of optimal operation of a gas transmission network. The natural gas flow network is modeled in [2–4,11] with daily and hourly limits on gas supply, demand, pipeline and storage. An approach for long-term expansion planning of combined gas and electricity networks is proposed in [12], which determines the timely and efficient allocation of resources (pipes vs. electricity transmission lines) in the expansion of energy networks. An operating strategy for short-term scheduling of gas-electricity integrated energy systems is proposed in [13] considering demand response and wind uncertainty. In [7,14,15], stochastic optimization models are proposed to address the uncertainties of various system components. In [16], optimization problems in natural gas transportation systems are analyzed, which demonstrate the necessity of optimal allocation of natural gas. However, in these existing literatures, economic dispatch of the two energy sectors is done ignoring the optimal allocation of natural gas supply.

To realize the optimal allocations of both electricity and natural gas, bi-level programming can be an effective method. In previous works, bi-level programming has been applied to optimal operation problems of power system [17–21]. In [17], the interactions between generation and load are considered in microgrid, in which the upper level is the energy-saving dispatch model and the lower level is the load control optimization model. Various methods of optimal operation of power system considering renewable energy, energy storage or electric vehicle are formulated as bi-level models in [18–20].

For power systems integrated with large-scale renewable energy, significant amounts of renewable energy generation are curtailed due to security restrictions. In this context, there has been widespread discussion of the power-to-gas (P2G) process whereby electrical energy can be converted to hydrogen (H_2) or synthetic natural gas (SNG), stored and recovered at a later time through combustion to generate low-carbon electricity and/or heat [22,23]. The P2G process not only helps avoid waste of renewable energy in electrical system due to system constraints, but also realizes the two-way coupling for the integrated gas and electrical systems, as shown in Fig. 1. Surplus renewable energy due to system constraints in electricity systems can be utilized to produce hydrogen or synthetic natural gas by the P2G process. From the perspective of long-term operation, the benefits of P2G are investigated in [23] in terms of wind curtailment and carbon emissions displacement, economic cost-saving associated with natural gas production, and congestion relief in both the gas and electrical networks. Grond et al. [24] analyzed the potential of a grid balancing system based on different combinations of traditional gas tur-

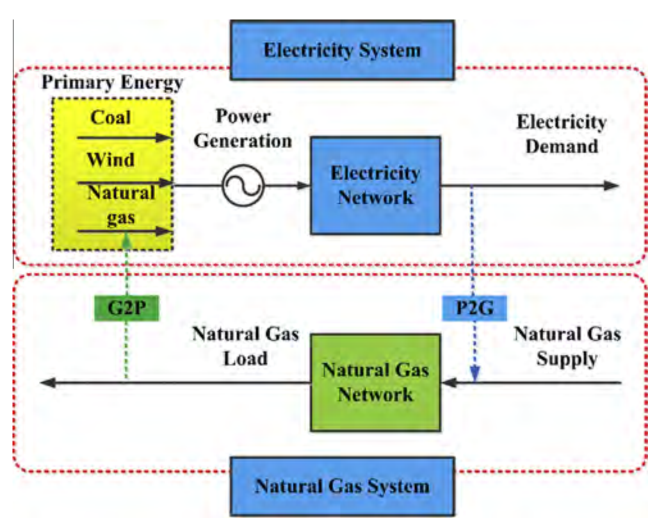

Fig. 1. Integrated natural gas and electricity network considering wind power and P2G.

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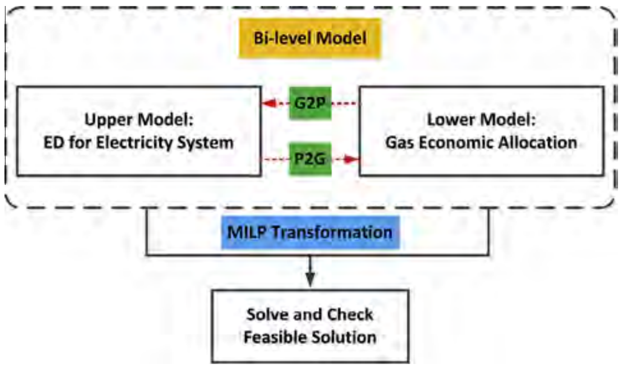

Fig. 2. Calculating strategy for ED of natural gas and electricity.

bines based power plants with innovative 'power-to-gas' plants. However, the P2G process has not been studied in short-term operations.

Based on the above premises, the aim of this paper is to study the short-term optimal operation of the integrated natural gas and electric power system with large-scale wind power as well as P2G process. The calculating strategy for ED of natural gas and electricity is as shown in Fig. 2. The natural gas transmission network is modeled and the security constraints are considered. The P2G process is modeled and introduced, which realizes the two-way coupling in the integrated systems and contributes to utilization of the curtailed wind power. The day-ahead economic dispatch for electric power and optimal allocation for natural gas are formulated as a bi-level optimization model. The upper-level model is formulated as an ED optimization model for electricity system, while the lower-level is the optimal allocation problem for natural gas system. The objective function is to minimize the total production cost for electricity and natural gas. The lower-level model is converted and added into the upper model as Karush-Kuhn-Tucher (KKT) optimality conditions, and then the bi-level model is transformed into a mixed-integer linear programming (MILP) problem. The major contributions of the paper are summarized as follows:

- Supply for both natural gas and electricity systems are dispatched economically and simultaneously by the joint system operator.
- A security-constrained bi-level economic dispatch model is proposed to minimize the day-ahead costs of electricity and natural gas consumptions respectively in the upper and lower levels. Then the bi-level model is transformed into a mix-integer linear programming (MILP) formulation, which has higher computing efficiency.
- Power-to-gas (P2G) process is modeled and introduced in the economic dispatch model, aiming at using curtailed wind power and achieving two-way coupling for the integrated energy systems.
- The results show that the P2G process is effective on improving the wind power utilization rate. It's also shown that the P2G process can contribute on the reduction of natural gas consumption and emission.

The rest of the paper is organized as follows: Section 2 introduces the bi-level economic dispatch model for integrated natural gas and electricity systems. The solution approach of the model is proposed in Section 3. Section 4 demonstrates the simulation results of case studies. Finally, conclusions are drawn in Section 5.

2. Bi-level economic dispatch model for integrated natural gas and electricity systems

In this paper, we assume the joint Independent System Operator (ISO) of the integrated natural gas and electricity systems take the responsibility to coordinate the economic dispatch to pursue the maximum profits for the whole system. The optimal allocation of natural gas to NGFGUs or other loads is determined by gas price of gas suppliers and market demands.

In this section, the bi-level ED model for the two-way coupled natural gas and electricity systems considering wind power and P2G process is presented, in which the security constraints and coupling constraints are imposed.

2.1. Upper-level model: economic dispatch model for electricity system

The objective function of the ED for electricity system is to minimize the total operation cost, including power generation cost, reserve cost, and wind curtailment compensation cost, as shown in (1):

$$\min\ f(P_{i,t}) = \sum_{t}^{T}\left(\sum_{i=1}^{N}(c_i \times P_{i,t}) + c_{wind} \times P_{wind,t} + \sum_{i=1}^{N}\eta_{i,sr} \times (P_{i\max} - P_{i,t}) + \pi_{cw} \times (P_{wind,t}^{forecast} - P_{wind,t})\right) \quad (1)$$

$$\text{s.t.}: \quad \sum_{i=1}^{N} P_{i,t} + P_{wind,t} = D_t \quad (2)$$

$$P_{i\min} \leqslant P_{i,t} \leqslant P_{i\max} \quad (3)$$

$$0 \leqslant P_{wind,t} \leqslant P_{wind,t}^{forecast} \quad (4)$$

$$P_{i,t} - P_{i,t-1} \leqslant Ramp_i^u * \Delta T \quad (5)$$

$$P_{i,t-1} - P_{i,t} \leqslant Ramp_i^d * \Delta T \quad (6)$$

$$\sum_{i=1}^{N}(P_{i\max} - P_{i,t}) \geqslant R_d + R_{up} \quad (7)$$

$$\sum_{i=1}^{N}(P_{i,t} - P_{i\min}) \geqslant R_{down} \quad (8)$$

$$-Limit_l \leqslant \sum_{i=1}^{N} GSF_{l-i} \times (P_{i,t} + P_{wind,t} - D_{i,t}) \leqslant Limit_l \quad (9)$$

The constraints are as shown in (2)–(8), and "s.t." is short for "subject to". The power balance constraint is given in (2). Power output limits of thermal units and wind power are shown in (3) and (4), where $P_{wind,t}^{forecast}$ denotes wind power forecasting output. Ramping and spinning reserve constraints are presented in (5)–(8). $Ramp_i^u$ and $Ramp_i^d$ are up and down ramping limits of thermal units. R_d is reserve requirements without wind power. R_{up} and R_{down} are the up and down reserve requirements to deal with wind power uncertainties. The transmission limits are shown in (9).

2.2. Lower-level model: economic allocation model for natural gas system

2.2.1. Objective function

The goal of the economic allocation for natural gas system is to minimize the gas purchasing cost from natural gas suppliers with different gas prices. The objective function is formulated as:

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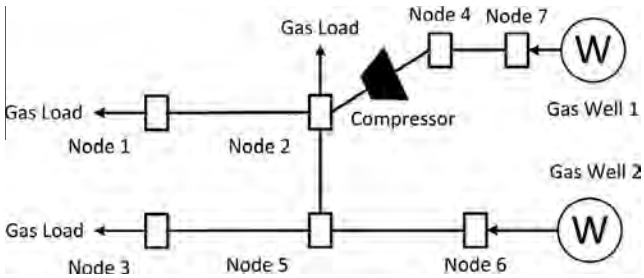

Fig. 3. Diagram of the seven-node natural gas system.

$$\min f(S_{m,t}) = \sum_{t}^{T}\sum_{m}^{M} \text{Price}_{m,gas} * S_{m,t} \tag{10}$$

2.2.2. Constraints of natural gas system

Fig. 3 describes a seven-node natural gas system with the key components including natural gas wells, transmission pipelines, and compressors.

(1) ***Gas supply and load:*** Similar to power generation and demand in the electricity system, gas supply and load are balanced and limited within reasonable ranges. Most of the gas is supplied by the gas wells, restricted by its upper and lower boundaries of the gas flow, which can be modeled as:

$$S_{m,\min} \leqslant S_{m,t} \leqslant S_{m,\max} \tag{11}$$

The gas load could be residential, commercial, or industrial, in which the gas load of natural gas-fired generating units plays a key role in the interconnection of the integrated systems. Corresponding to the upper and lower generation limits of NGFGUs, the gas load is also limited as:

$$GL_{\min} \leqslant GL_{m,gas,t} \leqslant GL_{\max} \tag{12}$$

(2) ***Pipeline flow:*** The pipeline flow is determined by the characteristics of the pipeline, e.g. the length, the diameter, the operating temperature, and the pressure difference between the associated nodes. The gas in a pipeline always flows from the node with higher pressure to the one with lower pressure. The nodal pressure is satisfied within certain range (14). The Weymouth equation is modeled as:

$$\begin{aligned} F_{\mathrm{nj}} &= \operatorname{sgn}(\pi_n, \pi_j) \cdot C_{nj}\sqrt{|\pi_n^2 - \pi_j^2|} \\ \operatorname{sgn}(\pi_n, \pi_j) &= \begin{cases} 1 & \pi_n \geqslant \pi_j \\ -1 & \pi_n < \pi_j \end{cases} \end{aligned} \tag{13}$$

$$\underline{\pi_n} \leqslant \pi_n \leqslant \overline{\pi_n} \tag{14}$$

In (13), C_{nj} is the pipeline constant related to the temperature, length, diameter, friction, and natural gas compositions. The sign function of *sgn* (π_n, π_j) indicates the direction of the gas flow through the pipeline. When the pressure of node n is higher than node j, it equals to 1, otherwise, it equals to −1.

In fact, the flow in one pipeline is related to the supply and load with virtually no loss. This paper defines the GSF_{gas} matrix to reflect the impact of nodal gas supply and load on the pipeline flow, which is similar to Generation Shift Factor (GSF_e) in the DC power flow model:

$$F_{nj} = \sum_{i=1}^{NG} GSF_{gas,m,nj} * (S_m - GL_m) \tag{15}$$

According to the GSF_{gas} matrix and gas supply and load of every node, the gas flow can be determined. The gas well with constant pressure is chosen as the slack node in the natural gas network. The Pipeline flow limit is shown in (16).

$$|F_{nj}| \leqslant Limit_{gas,nj} \tag{16}$$

(3) ***Compressor:*** Pressure loss occurs when natural gas flows through pipelines. Compressor stations are built to increase transmission efficiency and maintain the pressure levels of pipelines. Specifically, compressor stations are modeled by either fixed outlet pressure or fixed ratio similar to transformers [23]. In this paper, compressors are considered as fixed outlet pressure. We assume that the horse power of the compressors is supplied by the electricity network. In this case, the power consumption of compressors is regarded as an electricity load [13], and thus included in the total electricity load.

2.3. Coupling constraints of the integrated natural gas and electricity networks

Natural gas and electricity networks are two-way coupled and the energy flow is bi-directional: natural gas is consumed by NGFGUs for power generation, i.e. the gas-to-power (G2P) process, and on the contrary, electric power can be used to generate gas by P2G process.

2.3.1. Gas to power process and constraints

For electricity systems, natural gas is consumed by gas-fired units for power generation based on flexible contracts, and can be considered as gas loads. The gas consumption for power generation is considered as G2P process considering the conversion efficiency of NGFGU. The total gas consumption cannot exceed the signed contracts as shown in (18). The coupling constraints of G2P process can be described as follows:

$$P_{i,t,gas} = \eta_{G2P} * GL_{m,t,gas} \tag{17}$$

$$GL_{m,t,gas} \leqslant GL_{m,\max} \tag{18}$$

2.3.2. Power to gas process and constraints

The integration of P2G facilities enables the natural gas system to consume redundant electricity energy from power system, especially for surplus wind power. The chemical process can be described as: $2H_2O \rightarrow 2H_2 + O_2$, $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$. In the first step, gaseous hydrogen is formed by the process of electrolysis with certain efficiency. The technology of proton exchange membrane (PEM) [23,24] is considered to be favorable for the P2G process due to its faster ramping rates, which can better accommodate wind power fluctuations. H_2 generated in the first step can be stored for usage later or injected into the gas network blended with natural gas. In the second step, synthetic natural gas (SNG) is generated. As a secondary process for using the H_2, its efficiency will inevitably be lower than that of the first process. But the process of SNG consumes atmospheric CO_2, which achieves CO_2 emission reduction and more environmental benefits. Both of the processes can be achieved by consuming electric power (redundant wind power preferably) from the electricity system. In this paper, H_2 is considered to be totally used to generate SNG. P2G facilities can be considered as gas supplier using curtailed wind power with a certain efficiency, as shown in (19). Natural gas generated by P2G facilities are supposed to be stored temporarily and be injected into the natural gas system for the next dispatch period.

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The conversion from energy content to the volumetric quantity of SNG can be done using higher heating values (HHV) of natural gas, expressed as (20). The P2G facilities are limited by the upper bounds in (21).

$$E_{P2G,t,gas} = \eta_{P2G} * D_{m,t} \tag{19}$$

$$S_{P2G,t,gas} = E_{P2G,t,gas}/HHV_{gas} \tag{20}$$

$$0 \leqslant S_{P2G,t,gas} \leqslant \overline{S_{P2G,gas}} \tag{21}$$

3. Solution approach

To solve the proposed model, the bi-level optimization model is converted into a MILP formulation through the following methods.

(1) For the lower-level model, the formula of the pipeline flow and pressure difference between associated nodes is non-linear. To achieve the linearization of the model, in this paper, a linear computation process is proposed: the pipeline flows are calculated based on the GSF_{gas} matrix and gas nodal balance. According to the obtained pipeline flow values and the preset slack node pressure, node pressures can be obtained one by one, which can be shown as:

$$\pi_j = \sqrt{\pi_n^2 - (F_{nj}/\mathrm{sgn}(\pi_n, \pi_j) \cdot C_{nj})^2} \tag{22}$$

In this paper, the nodal pressure constraints are not considered in the optimization model directly and will be checked before output the optimal solution, which would simplify the optimization model without constraint violation.

(2) For the lower-level model, gas transferred by P2G can be considered as constant. Aiming at distinguishing the gas supply and SNG from P2G process, in this paper, SNG generated by P2G is considered as 'negative' gas demand, shown as

$$GL_{P2G,t,gas} = -D_{m,t}/\eta_{P2G} \tag{23}$$

Then the lower-level optimization model can be converted as:

$$\min\ f(S_{m,t}) = \sum_t^T \sum_m^M \mathrm{Price}_{m,gas} * S_{m,t} \tag{24}$$

$$\text{s.t.}: \quad \sum_m^M (S_{m,t} - GL_{m,t}) = GL_{P2G,t,gas} : \lambda_t \tag{25}$$

$$S_{m,\min} \leqslant S_{m,t} \leqslant S_{m,\max} : \omega_{m,t}^{\min}, \omega_{m,t}^{\max}, \quad \forall m = 1, 2, \ldots, M \tag{26}$$

$$-Limit_{gas,nj} \leqslant \sum_{m=1}^{NG} GSF_{gas,m,nj} \times (S_{m,t} - GL_{P2G,t,gas} - GL_{m,t}) \leqslant Limit_{gas,nj} : \quad \mu_{nj,t}^{\min}, \mu_{nj,t}^{\max}, \quad \forall n = 1, 2, \ldots, M \tag{27}$$

(3) The linearity of the lower-level model in (25)–(27) transfers the bi-level model into a single level Mathematic Program With Equilibrium Constraints (MPEC) problem by recasting the lower level problem as its KKT optimality conditions [25,26], which can be added into the upper level problem as a set of additional complementarity constraints. The MPEC model can be expressed as follows:

$$\mathrm{Max}\ -f(P_{i,t}) = -\sum_t^T \left(\sum_{i=1}^N (c_i \times P_{i,t}) + c_{wind} \times P_{wind,t} + \sum_{i=1}^N \eta_{i,sr} \times (P_{i\max} - P_{i,t}) + \pi_{cw} \times (P_{wind,t}^{forecast} - P_{wind,t}) \right) \tag{28}$$

$$\text{s.t.} \begin{cases} \sum_{i=1}^N P_{i,t} + P_{wind,t} = D_t \\ P_{i\min} \leqslant P_{i,t} \leqslant P_{i\max} \\ 0 \leqslant P_{wind,t} \leqslant P_{wind,t}^{forecast} \\ P_{i,t} - P_{i,t-1} \leqslant Ramp_i^u * \Delta T \\ P_{i,t-1} - P_{i,t} \leqslant Ramp_i^d * \Delta T \\ \sum_{i=1}^N (P_{i\max} - P_{i,t}) \geqslant R_d + R_{up} \\ \sum_{i=1}^N (P_{i,t} - P_{i\min}) \geqslant R_{down} \\ -Limit_l \leqslant \sum_{i=1}^N GSF_{l-i} \times (P_{i,t} + P_{wind,t} - D_{i,t}) \leqslant Limit_l \\ E_{P2G,t,gas} = \eta_{P2G} * D_{m,t} \\ S_{P2G,t,gas} = E_{P2G,t,gas}/HHV_{gas} \\ 0 \leqslant S_{P2G,t,gas} \leqslant \overline{S_{P2G,gas}} \\ \sum_m^M (S_{m,t} - GL_{m,t}) = GL_{P2G,t,gas} : \lambda_t \end{cases} \tag{29}$$

$$\mathrm{Price}_{m,gas} = \lambda + \sum_{nj=1}^L GSF_{gas,m,nj} \times (\mu_{nj,t}^{\min} - \mu_{nj,t}^{\max}) + \omega_{m,t}^{\min} - \omega_{m,t}^{\max} \tag{30}$$

$$0 \leqslant \mu_{nj,t}^{\min} \perp Limit_{gas,nj} + \sum_{m=1}^{NG} GSF_{gas,m,nj} * (S_{m,t} - GL_{P2G,t,gas} - GL_{m,t}) \geqslant 0 \tag{31}$$

$$0 \leqslant \mu_{nj,t}^{\max} \perp Limit_{gas,nj} - \sum_{m=1}^{NG} GSF_{gas,m,nj} * (S_{m,t} - GL_{P2G,t,gas} - GL_{m,t}) \geqslant 0 \tag{32}$$

$$0 \leqslant \omega_{m,t}^{\min} \perp S_{m,t} - S_{m,\min} \geqslant 0 \tag{33}$$

$$0 \leqslant \omega_{m,t}^{\max} \perp S_{m,\max} - S_{m,t} \geqslant 0 \tag{34}$$

(4) The MPEC model in (28)–(34) is nonlinear due to the complementarity constraints (31)–(34). Utilizing the method in [27], the model can be further converted to a MILP problem, given by:

$$\mathrm{Max}\ -f(P_{i,t}) = -\sum_t^T \left(\sum_{i=1}^N (c_i \times P_{i,t}) + c_{wind} \times P_{wind,t} + \sum_{i=1}^N \eta_{i,sr} \times (P_{i\max} - P_{i,t}) + \pi_{cw} \times (P_{wind,t}^{forecast} - P_{wind,t}) \right) \tag{35}$$

$$\text{s.t.}\begin{cases} \sum_{i=1}^{N} P_{i,t} + P_{wind,t} = D_t \\ P_{i\min} \leqslant P_{i,t} \leqslant P_{i\max} \\ 0 \leqslant P_{wind,t} \leqslant P_{wind,t}^{forecast} \\ P_{i,t} - P_{i,t-1} \leqslant Ramp_i^u * \Delta T \\ P_{i,t-1} - P_{i,t} \leqslant Ramp_i^d * \Delta T \\ \sum_{i=1}^{N} (P_{i\max} - P_{i,t}) \geqslant R_d + R_{up} \\ \sum_{i=1}^{N} (P_{i,t} - P_{i\min}) \geqslant R_{down} \\ -Limit_l \leqslant \sum_{i=1}^{N} GSF_{l-i} \times (P_{i,t} + P_{wind,t} - D_{i,t}) \leqslant Limit_l \\ E_{P2G,t,gas} = \eta_{P2G} * D_{m,t} \\ S_{P2G,t,gas} = E_{P2G,t,gas} / HHV_{gas} \\ 0 \leqslant S_{P2G,t,gas} \leqslant \overline{S_{P2G,gas}} \\ \sum_{m}^{M} (S_{m,t} - GL_{m,t}) = GL_{P2G,t,gas} : \lambda_t \\ \text{Price}_{m,gas} = \lambda + \sum_{nj=1}^{L} GSF_{gas,m,nj} \times (\mu_{nj,t}^{\min} - \mu_{nj,t}^{\max}) + \omega_{m,t}^{\min} - \omega_{m,t}^{\max} \end{cases} \quad (36)$$

$$0 \leqslant \mu_{nj,t}^{\min} \leqslant M_{\mu,t}^{\min} v_{\mu,nj,t}^{\min} \quad (37)$$

$$0 \leqslant Limit_{gas,nj} + \sum_{m=1}^{NG} GSF_{gas,m,nj} * (S_{m,t} - GL_{P2G,t,gas} - GL_{m,t}) \leqslant M_{\mu,t}^{\min}(1 - v_{\mu,nj,t}^{\min}) \quad (38)$$

$$0 \leqslant \mu_{nj,t}^{\max} \leqslant M_{\mu,t}^{\max} v_{\mu,nj,t}^{\max} \quad (39)$$

$$0 \leqslant Limit_{gas,nj} - \sum_{m=1}^{NG} GSF_{gas,m,nj} * (S_{m,t} - GL_{P2G,t,gas} - GL_{m,t}) \leqslant M_{\mu,t}^{\max}(1 - v_{\mu,nj,t}^{\max}) \quad (40)$$

$$0 \leqslant \omega_{m,t}^{\min} \leqslant M_{\omega,t}^{\min} v_{\omega,m,t}^{\min} \quad (41)$$

$$0 \leqslant S_{m,t} - S_{m,\min} \leqslant M_{\omega,t}^{\min}(1 - v_{\omega,m,t}^{\min}) \quad (42)$$

$$0 \leqslant \omega_{m,t}^{\max} \leqslant M_{\omega,t}^{\max} v_{\omega,m,t}^{\max} \quad (43)$$

$$0 \leqslant S_{m,\max} - S_{m,t} \leqslant M_{\omega,t}^{\max}(1 - v_{\omega,m,t}^{\max}) \quad (44)$$

(5) After solving the bi-level optimization model, the nodal pressures are calculated and judged. At the same time, the feasibility of the solution is checked. If feasible, output the solution, otherwise, apply a modification to the solution and solve the model again.

4. Case studies

In this section, case studies on the PJM 5-bus power system [28] with 7-node gas system [7] and the IEEE 118-bus power system [29] with Belgian natural gas network [10] are applied to demonstrate the effectiveness of the proposed bi-level ED model. The MILP formulation and algorithms were implemented in the General Algebraic Modeling System (GAMS) [30] on a PC with Intel Core i7 3.00 GHz CPU and 8 GB RAM and the optimization was carried out using CPLEX 12.5 [31].

4.1. PJM 5-bus system

The PJM 5-bus system is depicted in Fig. 4, in which the generation capacity and bid prices are also included. A 400 MW wind farm is installed at Bus E, and its bid cost is set to $ 8. The load is equally distributed on three load buses. The natural gas system is given in Fig. 3, which has 7 nodes, 5 pipelines, 1 compressor, 2 natural gas suppliers, and 3 natural gas loads. The parameters can be found in [14]. Part of natural gas loads at nodes 1–3 are corresponding to the hourly generation dispatch of the three NGFGUs at Bus A and Bus D. Another part of natural gas loads (residential gas load) and electricity load are shown in Fig. 5. P2G facilities are integrated at Bus B in the PJM 5-bus system and node 5 in the natural gas system with an efficiency of 64% for the SNG production [23]. The electric power used by the P2G facility is supposed to be equal to forecasting output minus dispatched output of wind power for the convenience of the study.

To demonstrate the effectiveness of the proposed bi-level optimization model, the following cases are discussed:

4.1.1. Impact of natural gas system security constraints

In the natural gas system, the gas flows from one node to another through pipelines with pressure loss. The security constraints ensure that the gas network operates within feasible regions. The dispatch results of the three NGFGUs and wind power with and without the security constraints of natural gas system are shown in Figs. 6 and 7, and pressures of the node 3 (important gas load node) are shown in Fig. 8.

In Figs. 6 and 7, it can be observed that the scheduling results are different during some dispatch periods with and without the security constraints of natural gas system. In the first six hours,

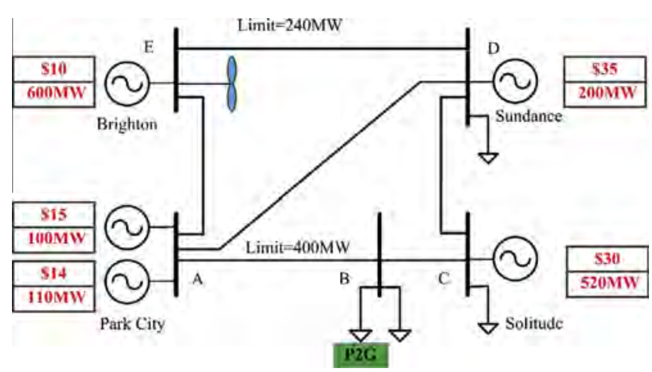

Fig. 4. PJM 5-bus system.

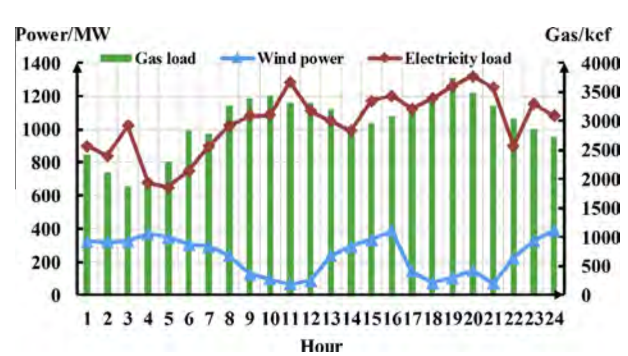

Fig. 5. Wind power forecasting output, electricity load and gas load.

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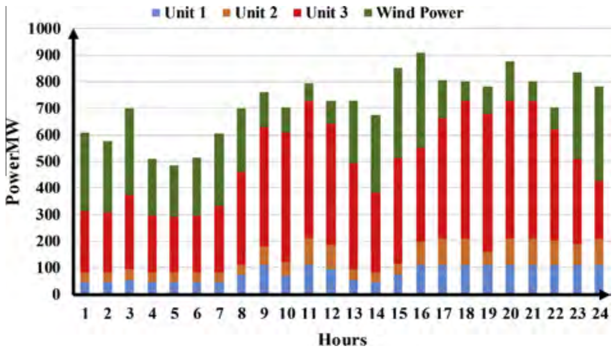

Fig. 6. Dispatching results with security constraints.

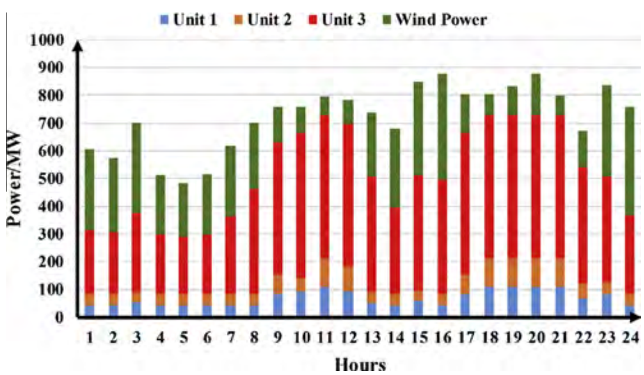

Fig. 7. Dispatching results without security constraints.

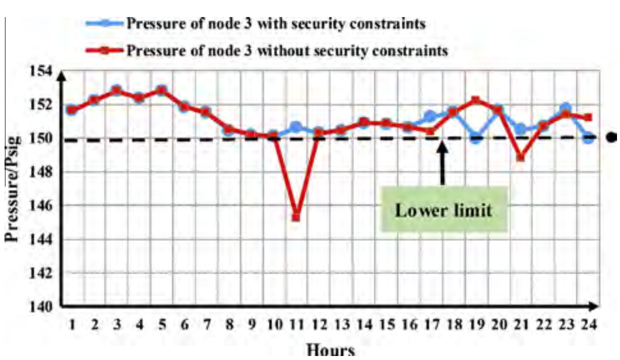

Fig. 8. Pressure comparison of node 3.

the dispatched outputs of Unit 3 are the same in the two scenarios since the operating states are within bounds. But at hour 7–10, the dispatched outputs of Unit 3 are reduced considering the security constraints, which indicates that the security constraints of natural gas system impose restrictions on the operation of the integrated energy system. Fig. 8 shows that the pressures of node 3 go beyond the lower limit without considering security constraints of natural gas system at hour 11 and 21, while no violations occur in the other case. The results show that the security constraints of natural

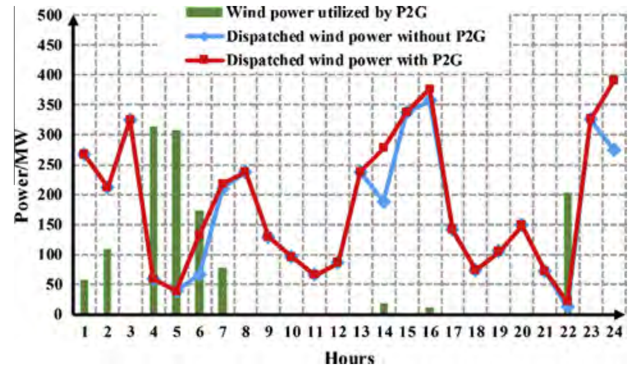

Fig. 9. Comparison of dispatched wind power.

gas system should be considered in the optimal operation of the integrated energy system.

4.1.2. Impact of P2G process

The P2G process considered in this paper can accommodate the redundant wind power to produce natural gas. It is an indirect way for wind power utilization. The comparison of the dispatch results with/without P2G process is listed in Table 1. The comparison of dispatched wind power is shown in Fig. 9. It can be observed from Table 1 that the total operation cost for power system is reduced by 5541.1$ during 24 h. The total natural gas generated by P2G process reaches 2604.3 kcf. The direct wind power utilization is increased from 72.0% to 77.5% due to the P2G process. The reason lies in that the natural gas generated by P2G process satisfies part of gas demands and mitigate the impact of gas network constraints on the dispatch results. Higher wind power utilization decreases the output of NGFGUs and part of natural gas demands are met by P2G process, which results in 12979.6 kcf reduction on natural gas consumption. Fig. 9 shows that the dispatched wind power with P2G at each hour is not less than that of the case without P2G.

In addition to the improvement on wind power utilization and reduction on natural gas consumption, another benefit of P2G process is emission reduction. According to [23], the resulting CO_2 emission reduction from synthetic natural gas production from P2G is 180 kg/MW h. Hence, the total CO_2 emission reduction during 24 h is 227,600 kg.

It can be concluded that the introduction of P2G process in the optimal operation of the integrated energy systems can increase energy utilization efficiency, reduce energy consumption and emission, and improve the operating economy of the system. The results show the advantages of P2G process, and verify the feasibility for the reasonability of optimal operation strategy proposed in this paper.

4.1.3. Impact of fluctuating natural gas loads

There is a high probability that natural gas flow congestion or pressure loss occurs when the residential gas load peaks. In this case, the constant and fluctuating residential gas loads are applied to the model to reflect the impact of the fluctuating natural gas loads. Constant gas loads are assumed to be 1880 kcf and 3740 kcf, while the fluctuating loads are as shown in Fig. 5. The hourly dispatch results of gas-fired unit 3 for the three scenarios are

Table 1
Comparison of results with/without P2G process.

	Costs of electricity system ($)	Gas consumption (kcf)	Wind power utilization	Gas from P2G (kcf)
Without P2G	531860.8	154185.8	72.00%	0
With P2G	526319.7	141206.2	77.5%	2604.3

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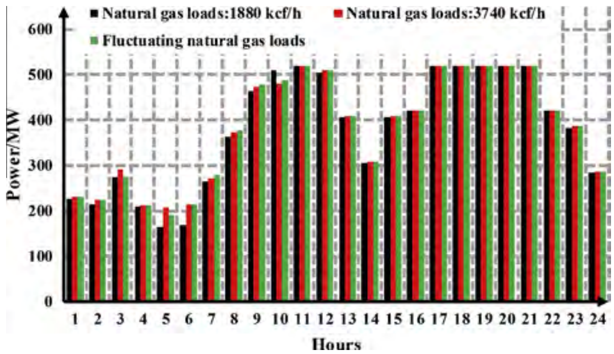

Fig. 10. Comparison of hourly dispatch of unit 3.

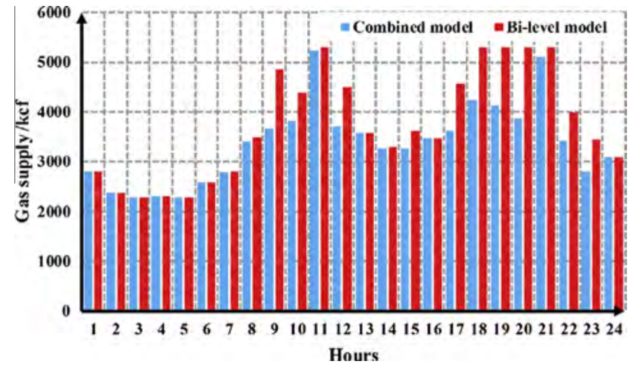

Fig. 11. Comparison of gas supply from gas well 1.

Table 2
Comparison of results of bi-level and combined model.

	Costs of electricity system ($)	Gas consumption (kcf)	Wind power utilization	Gas from P2G (kcf)
Bi-level	526319.7	141206.2	77.5%	2604.3
Combined	533945.1	129068.2	74.5%	2956.0

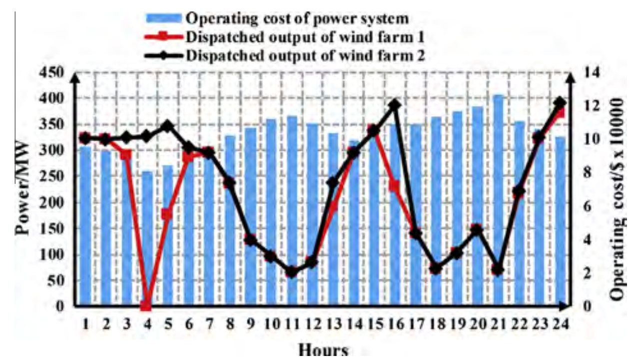

Fig. 12. Operating costs and dispatched wind power.

depicted in Fig. 10. It can be observed that the hourly residential natural gas load can affect the optimal operation of power systems.

4.1.4. Effectiveness of the bi-level optimization model

The bi-level optimization model in this paper aims at day-ahead economic dispatch for integrated energy system, realizing optimal energy allocation for the power system and natural gas system simultaneously. In order to verify effectiveness of the bi-level optimization model, the combined MILP model followed is carried out as a comparative study.

$$\begin{aligned} &Min \quad \text{Eq. (1)} + \text{Eq. (10)} \\ s.t.\ &\text{Eqs. (2)–(8), Eqs. (17)–(21), Eq. (23), Eqs. (25)–(27)} \end{aligned}$$

Table 2 compares the results of the bi-level and combined models. The operation costs of power system obtained by the bi-level model are lower and the wind power utilization rate is higher, indicating more gas generation from P2G. More natural gas is consumed in the case of combined model. In the natural gas system, the gas well 1 is the cheaper one. Fig. 11 shows the comparison of gas supply from gas well 1. In all dispatching periods, the gas supplies from gas well 1 in the case of bi-level model are no less than those of combined model, which corresponds to better economy. This comparison verifies the effectiveness and superiority of the proposed bi-level model.

The computational time of the bi-level model on this integrated energy system is 0.035 s, which perfectly satisfies the requirements of practical implementation.

4.2. IEEE 118-bus system

The IEEE 118-bus system is applied here to further demonstrate the applicability of the proposed model on large systems. This system consists of 118 buses, 54 generators and 186 branches. The generator bidding data are similar with those in [32]: 20 low-cost generators with bids from $10 to $19.5 with $0.5 increment; 20 expensive generators with bids from $30 to $49 with $1 increment; and 14 most expensive generators with bidding from $70 to $83 with $1 increment. The Belgian natural gas network is modified by different factors to match the case. P2G is connected at node 16. Nine generators are assumed to be gas fired units. Two wind farms are connected at Bus 3 and Bus 5 with the same forecasting output as that in PJM 5-bus system. The hourly electricity loads are then multiplied by different factors to match the installed energy generation.

The hourly operating costs and dispatched wind power are shown in Fig. 12. The computational time of the proposed bi-level model on this large integrated energy system is 15.725 s. The results verify the effectiveness of the proposed bi-level model on large integrated energy systems.

In conclusion, the results of case studies demonstrate that the bi-level optimization model is effective for small and large systems, and the integration of P2G process can increase energy efficiency, reduce energy consumption and emission, and improve the operating economy of the system. In China, the curtailment rate reached 15–25% in the Northern and Northeastern provinces (where more than 75% of the wind power capacity is installed) [33]. Under such background and with the development of NGFGUs and P2G technology, the optimal dispatch strategy proposed in this paper would be easier to be implemented to help system operators with the decision-making process.

5. Concluding remarks

This paper presents a security-constrained economic dispatch model for integrated natural gas and electricity systems considering wind power and power-to-gas process. The optimal allocation of electricity and natural gas is formulated as a bi-level optimization model and assumed to be calculated by the joint operator. The contributions are summarized as follows:

(1) The mathematical model of the integrated natural gas and electricity systems is presented. Security constraints of both networks and the coupling constraints are introduced. Sup-

ply for both natural gas and electricity systems is dispatched economically and simultaneously by the joint system operator.

(2) The optimal energy dispatch of the integrated natural gas and electricity systems is formulated as a bi-level optimization model, in which the economic dispatch of power system and optimal allocation of natural gas are done simultaneously. The bi-level model is converted into a MILP formulation, and the computational time of the bi-level model satisfies the requirements of the practical implementation.

(3) P2G process is incorporated into the optimal operation of the integrated natural gas and electricity systems in purpose of utilizing the redundant wind power. P2G and NGFGUs realize the bidirectional interactions of the integrated systems.

(4) Two case studies are carried out to verify the effectiveness of the model. The results show that the P2G process is effective on improving the wind power utilization rate. It's also shown that the P2G process can contribute on the reduction of natural gas consumption and emission.

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References

[1] Robert RE, Croissant MP, Masih JR. International energy outlook: U.S. department of energy. Wash Quart 1996;19(4):70–99.
[2] Correa-Posada CM, SáNchez-Martın P. Security-constrained optimal power and natural-gas flow. IEEE Trans Power Syst 2014;29(4):1780–7.
[3] Liu C, Shahidehpour M, Wang J. Application of augmented lagrangian relaxation to coordinated scheduling of interdependent hydrothermal power and natural gas systems. IET Gener Transm Distrib 2010;4(12):1314–25.
[4] Liu C, Shahidehpour M, Li Z, Fotuhi-Firuzabad M. Component and mode models for the short-term scheduling of combined-cycle units. IEEE Trans Power Syst 2009;24(2):976–90.
[5] Qadrdan M, Chaudry M, Jenkins N, Baruah P, Eyre N. Impact of transition to a low carbon power system on the GB gas network. Appl Energy 2015;151:1–12.
[6] Li T, Eremia M, Shahidehpour M. Interdependency of natural gas network and power system security. IEEE Trans Power Syst 2008;23(4):1817–24.
[7] Alabdulwahab A, Abusorrah A, Zhang X, Shahidehpour M. Coordination of interdependent natural gas and electricity infrastructures for firming the variability of wind energy in stochastic day-ahead scheduling. IEEE Trans Sust Energy 2015;6(2):606–15.
[8] Wu L, Shahidehpour M. Optimal coordination of stochastic hydro and natural gas supplies in midterm operation of power systems. IET Gener Transm Distrib 2011;5(5):577–87.
[9] Unsihuay C, Lima JWM, De Souza ACZ. Modeling the integrated natural gas and electricity optimal power flow. In: IEEE PES General Meeting, vol. 1; 2007. p. 1–7.
[10] De Wolf D, Smeers Y. The gas transmission problem solved by an extension of the simplex algorithm. Manage Sci 2000;46(11):1454–65.
[11] Cui H, Li F, Hu Q, Bai L, Fang X. Day-ahead coordinated operation of utility-scale electricity and natural gas networks considering demand response based virtual power plants. Appl Energy 2016;176:183–95.
[12] Chaudry M, Jenkins N, Qadrdan M, Wu J. Combined gas and electricity network expansion planning. Appl Energy 2014;113(6):1171–87.
[13] Bai L, Li F, Cui H, Jiang T, Sun H, Zhu J. Interval optimization based operating strategy for gas-electricity integrated energy systems considering demand response and wind uncertainty. Appl Energy 2016;167:270–9.
[14] Zhang X, Shahidehpour M, Alabdulwahab A, Abusorrah A. Hourly electricity demand response in the stochastic day-ahead scheduling of coordinated electricity and natural gas networks. IEEE Trans Power Syst 2015;31(1):1–10.
[15] Jirutitijaroen P, Kim S, Kittithreerapronchai O, Prina J. An optimization model for natural gas supply portfolios of a power generation company. Appl Energy 2013;107(5):1–9.
[16] Ríos-Mercado RZ, Borraz-Sánchez C. Optimization problems in natural gas transportation systems: a state-of-the-art review. Appl Energy 2015;147:536–55.
[17] Liu J, Li J. A bi-level energy-saving dispatch in smart grid considering interaction between generation and load. IEEE Trans Smart Grid 2015;6(3):1443–52.
[18] Hu Z, Zhang M, Wang X, Li C, Hu M. Bi-level robust dynamic economic emission dispatch considering wind power uncertainty. Electric Power Syst Res 2016;135:35–47.
[19] Ju L, Tan Z, Yuan J, Tan Q, Li H, Dong F. A bi-level stochastic scheduling optimization model for a virtual power plant connected to a wind–photovoltaic–energy storage system considering the uncertainty and demand response. Appl Energy 2016;171:184–99.
[20] Škugor B, Deur J. A bi-level optimisation framework for electric vehicle fleet charging management. Appl Energy 2016. http://dx.doi.org/10.1016/j.apenergy.2016.03.091.
[21] Feijoo F, Das TK. Emissions control via carbon policies and microgrid generation: a bilevel model and Pareto analysis. Energy 2015;90:1545–55.
[22] Department of Energy and Climate Change. The Future of Heating: Meeting the Challenge. London (UK): HM Government; 2013. March.
[23] Clegg S, Mancarella P. Integrated modeling and assessment of the operational impact of power-to-gas (P2G) on electrical and gas transmission networks. IEEE Trans Sust Energy 2015;6(4):1234–44.
[24] Grond L, Schulze P, Holstein J, Systems analyses power to gas: technology review. DNV KEMA energy sustainability, Tech. Rep. GCS 13.R.23579. Groningen (The Netherlands); 2013.
[25] Kardakos EG, Simoglou CK, Bakirtzis AG. Optimal bidding strategy in transmission-constrained electricity markets. Electric Power Syst Res 2014;109(4):141–9.
[26] Fang X, Hu Q, Li F, Wang B. Coupon-based demand response considering wind power uncertainty: a strategic bidding model for load serving entities. IEEE Trans Power Syst 2015;31(2):1–13.
[27] Fortuny-Amat J, McCarl B. A representation and economic interpretation of a two-level programming problem. J Oper Res Soc 1981;32(9):783–92.
[28] Li F, Bo R. DCOPF-based LMP simulation: algorithm, comparison with ACOPF and sensitivity. IEEE Trans Power Syst 2008;22(4):1475–85.
[29] Power System Test Case Archive. University of Washington <http://www.ee.washington.edu/research/pstca/>.
[30] General Algebraic Modeling System (GAMS) <http://www.gams.com/>.
[31] ILOG CPLEX, ILOG CPLEX Homepage; 2009 <http://www.ilog.com>.
[32] Wei Y, Li F, Tomsovic K. Measuring the volatility of wholesale electricity prices caused by wind power uncertainty with a correlation model. IET Renew Power Gener 2012;6(5):315–23.
[33] Chen X, Kang C, O'Malley M, Xia Q. Increasing the flexibility of combined heat and power for wind power integration in china: modeling and implications. IEEE Trans Power Syst 2015;30(4):1848–57.

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