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Optimal low-carbon economic environmental dispatch of hybrid electricity-natural gas energy systems considering P2G

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Abstract: Power to gas facilities (P2G) could absorb excess renewable energy that would otherwise be curtailed due to electricity network constraint by converting it to methane (synthetic natural gas). The produced synthetic natural gas can power gas turbines and realize bidirectional energy flow between power and natural-gas system. P2G therefore has significantly potential of unlocking inherent flexibility of the integrated system, but also pose new challenges of increased system complexity. Coordinated operation strategy that manages power and natural-gas network constraints together is essential to address such challenge. In this paper, a novel low-carbon economic environmental dispatch strategy is presented considering all the constraints in both systems. The multi-objective black-hole particle swarm optimization algorithm (MOBHPSO) is adopted. In addition to P2G, gas demand management strategy is proposed to support gas flow balance. A new solving approach that combines effective redundancy method, trust region method and Levenberg-Marquardt method is proposed to address the complex coupled constraints. Case studies that use integrated IEEE 39-bus power and Belgian high-calorific 20-node gas system demonstrate the effectiveness and scalability of the proposed model and optimization method. The analysis of dispatch results illustrates the benefit of P2G in the wind power accommodation, low-carbon, economic and environmental improvement of integrated system operation.

Keywords: hybrid electricity-natural gas energy systems; power to gas (P2G); low-carbon; economic environmental dispatch; trust region method; Levenberg-Marquardt method

1. Introduction

With further acceleration of the low-carbon energy process, as well as the energy crisis, environmental pollution and other issues, the capacity of renewable energy sources is increased continuously. While, due to the intermittency and uncertainty of wind power as well as the lack of peak load regulation of power system, it is likely that more and more wind power generation will have to be curtailed in order to maintain the power system reliability [1]. To solve this problem, much research is carried out to explore practical means to reduce the curtailment of wind power generation. With the growing interdependence of power system and natural-gas system and the development of power to gas technologies [2-8], it creates operational interactions between power system and natural-gas system which could obtain additional benefits for both systems including reducing the curtailed wind power generation. On the one hand, the power system tends to require more flexible power energy from the natural-gas system to shift peak load whereby the gas-fired...
units [3], which is conducive to the accommodation of wind power. On the other hand, the natural-gas system absorbs methane or hydrogen produced by P2G to guarantee the continuity of gas supply and the wind power energy will be stored and transported in the existing natural-gas system for generating low-carbon electricity or heat later [9-11], which uses the curtailed wind power directly. Therefore, the integrated electricity-natural gas energy systems with P2G have become one of the effective forms to reduce the curtailment of wind power generation.

The diagram of integrated electricity-natural gas energy systems with P2G is shown in Figure 1. It can be seen that the power system and the natural-gas system exchange the energy whereby P2G and gas-fired units. When the curtailed wind power is converted to hydrogen or methane whereby power to hydrogen facilities (P2H) or power to methane facilities (P2M), P2G which includes P2H and P2M is the load of power system and the gas source of natural-gas system. Meanwhile, the gas-fired units are the load of natural-gas system and the generators of power system. Obviously, operation parameters of P2G, power system and natural-gas system are interrelated and interactive which can affect the operation cost, CO2 emissions, reliability and stability of both systems. Therefore, how to deal with the interactive relationship between power system and natural-gas system and how to achieve coordinated optimal operation with economic environmental benefits are the key issues for the integrated power system and natural-gas system.

For the integrated electricity-natural gas energy systems, the initial research is focused on optimal power flow [12-15], unit commitment [16], optimal dispatch [17-19] and steady-state analysis [20] and system planning [21]. For the calculation of optimal power flow, the total operation cost is usually considered as optimal objective and the dual interior point method [12], the Monte Carlo method [13], the point estimation method [14] are adopted frequently. Some studies introduce energy hub to deal with the translation of different energies in the hybrid electricity-natural gas energy systems [13,17]. For the optimization of system operation, the operation of power system and the operation of natural-gas system are mostly optimized separately using the deterministic optimization methods or stochastic optimization methods [18]. For the steady-state analysis of the hybrid electricity-natural gas energy systems, basing on the steady-state analysis of power system, the analysis model of natural-gas system is realized by analogy analysis between power system and natural-gas system, and then the comprehensive steady-state analysis model of hybrid electricity-natural gas energy systems is given [20]. For the optimal system planning, a chance constrained programing approach is presented to minimize the investment cost of the integrated energy systems [21]. In these studies, P2G is not considered. While, as the coupling operation link of the power system and natural-gas system, P2G plays a more and more important role in wind power
accommodation with broad prospects and potential for energy development [22-24]. Therefore, it is necessary to carry out the research on optimal operation of integrated electricity-natural gas energy systems considering P2G. The early studies on P2G are mainly focused on technology implementation and security application [6, 25-28]. Recently, although some achievements about optimal operation of integrated electricity-natural gas energy systems considering P2G have been achieved [6-8, 24,29-38], it still seems to be in the exploratory stage from the following aspects.

(1) Optimal objectives: The minimum total operation cost is mostly adopted [6, 24,29-32,37]. Only in a few studies, the maximum wind power accommodation [33] or the minimum energy purchase cost [34] or net power demand smoothness [38] is also considered as the objective. While, environmental benefit is rarely considered. As we know, the low-carbon and emission reduction requirements become more and more important. So it is necessary to take environmental benefit into consideration.

(2) Optimal models: The operation model of power system and operation model of natural-gas system are mainly established separately basing on the two-level optimal power flow structure [6, 30-32]. It seems that rare consideration is given to coordinated optimization between the two energy systems.

(3) Optimal algorithms: Generally, the traditional algorithms are adopted in most studies, such as mix-integer linear programming method [3,24], mixed-integer quadratic programming method [37] and interior point method [35]. While, the intelligent optimization algorithms with high global search ability and fast convergence speed are rarely used.

(4) Constraints handling methods: The constraints handling methods affect the operation results directly. While, few articles give full details about the constraints handling methods, especially for the complicated dynamic nodal balance constraint and volume limits of gas storage in the natural-gas system.

On the above premises, this paper establishes the optimal operation model of the hybrid electricity-natural gas energy systems considering operation cost, natural-gas cost reduction due to P2G, CO2 emissions and SOx emissions to achieve low-carbon, economic and environmental benefits. The multi-objective black-hole particle swarm optimization algorithm (MOBHPSO) [39-42] is adopted. The power flow is calculated using Newton-Raphson method. And the non-linear gas flow equations are solved by trust region method [43-44] and Levenberg-Marquardt (L-M) method [45-46], respectively. The gas demand management strategy is proposed to balance the gas flow. Moreover, the detailed handling methods of inequality constraints in natural-gas system are also given in this paper. Several case studies are carried out on a hybrid IEEE 39-bus power system and Belgian high-calorific 20-node gas system in a period of 24 hours to investigate the low-carbon, economic and environmental benefits of P2G in terms of cost reduction (6.165×105$), rate decline of wind curtailment (from 24.85% to 4.04%), CO2 emissions reduction (3630 ton) and SOx emissions reduction (0.254 ton).

2. Problem Formulation

The optimal low-carbon economic environmental dispatch problem of hybrid electricity-natural gas energy systems with P2G is a complicated non-convex, coupled, non-linear, multi-objective and multi-constraint optimization problem. It contains three parts: the first one is the optimization of power system; the second one is the optimization of natural-gas system; and the last one is the coordination of the hybrid electricity-natural gas energy systems. The flow chart of this optimization problem is shown in Figure 2. Each part of the flow chart will be described in details.

2.1 Optimal economic environmental dispatch of power system

2.1.1 Objectives
\[ \text{Min } F_p = \sum_{i=1}^{N_G} \sum_{t=1}^{T} a_i P_{Gi}(t)^2 + b_i P_{Gi}(t) + c_i \]  

(1)

\[ \text{Min } E_{SOx} = \sum_{i=1}^{N_G} \sum_{t=1}^{T} (\alpha_i + \beta_i P_{Gi}(t) + \gamma_i P_{Gi}(t)^2 + \delta_i e^{\lambda_i P_{Gi}(t)}) \]  

(2)

\[ \text{Min } L_p = \sum_{t=1}^{T} P_L(t) + \sum_{k=1}^{N_{P2G}} P_{P2G,k}(t) - \sum_{i=1}^{N_G} P_{Gi}(t) \]  

(3)

Where \( F_p \) is the fuel cost of power system; \( N_G \) is the number of power generations; \( T \) is the number of time periods; \( P_{Gi}(t) \) is the power generation output at time \( t \); \( a_i, b_i, c_i \) are coefficient of the fuel cost; \( E_{SOx} \) is the pollutant emission of \( SOx \); \( \alpha_i, \beta_i, \gamma_i, \delta_i, \lambda_i \) are coefficient of the pollutant emission; \( L_p \) is the load loss rate presenting the reliability of power supply; \( N_{P2G} \) is the number of P2G; \( P_L(t) \) is the power load at time \( t \); \( P_{P2G}(t) \) is the power supplied to the P2G facilities at time \( t \).

The power output of gas-fired units is calculated by the product of the gas flow injected to the gas-fired units \( Q_{GT}(t) \), higher heating value of natural gas \( HHV_g \) and the energy conversion efficiency \( \eta_{GT}(t) \). In this paper, the last objective is converted into a constraint by being less than a given value \( \varepsilon \).

---

**Figure 2. Flow chart**
2.1.2 Constraints

(1) Power output limits

\[ P_{\text{Gi}}^{\text{min}} \leq P_{\text{Gi}}(t) \leq P_{\text{Gi}}^{\text{max}} \]  

(4)

Where \( P_{\text{Gi}}^{\text{min}} \) and \( P_{\text{Gi}}^{\text{max}} \) represent the minimum power output and maximum power output of unit \( i \), respectively.

(2) Ramp rate limits

\[
\begin{align*}
P_{\text{Gi}}(t) &\geq \max\{P_{\text{Gi}}^{\text{min}}, P_{\text{Gi}}(t-1) - \Delta P_{\text{Gi}}^{\text{down}}\}, & P_{\text{Gi}}(t) \leq P_{\text{Gi}}(t-1) \\
\end{align*}
\]

(5)

where \( \Delta P_{\text{Gi}}^{\text{up}} \) and \( \Delta P_{\text{Gi}}^{\text{down}} \) represent the ramp up rate and the ramp down rate of unit \( i \), respectively.

(3) Line capacity limit

\[ S_l(t) \leq S_l^{\text{max}} \]  

(6)

where \( S_l^{\text{max}} \) is the maximum capacity of line \( l \).

2.2 Optimal low-carbon economic dispatch of natural-gas system considering P2G

2.2.1 Objectives

(1) Minimum the operational cost of natural-gas system

\[
\begin{align*}
\text{Min} & \quad C_{\text{well}} + C_{\text{gs}} + C_{\text{P2G}} - S_{\text{P2G}} \\
C_{\text{well}} &\doteq \sum_{n=1}^{N_{\text{w}}} \sum_{t=1}^{T} Q_{\text{wn}}(t)u_{\text{wn}}(t) \\
C_{\text{gs}} &\doteq \sum_{m=1}^{N_{\text{gs}}} \sum_{t=1}^{T} Q_{\text{gs,m}}(t)u_{\text{gs,m}}(t) \\
C_{\text{P2G}} &\doteq \sum_{k=1}^{N_{\text{P2G}}} \sum_{t=1}^{T} P_{\text{P2G,k}}(t)u_{\text{P2G,k}} \\
S_{\text{P2G}} &\doteq \sum_{k=1}^{N_{\text{P2G}}} \sum_{t=1}^{T} Q_{\text{P2G,k}}(t)u_{\text{P2G,k}} \\
\end{align*}
\]

(7)

Where \( C_{\text{well}} \), \( C_{\text{gs}} \), \( C_{\text{P2G}} \) represent the operation cost of gas wells, the operation cost of gas storage, the operation cost of P2G, respectively. \( S_{\text{P2G}} \) is the saved natural-gas cost due to the P2G. \( N_{\text{w}}, N_{\text{gs}} \) represent the number of gas wells and the number of gas storage, respectively; \( Q_{\text{wn}}(t) \) is the gas flow of gas well \( n \) at time \( t \); \( Q_{\text{gs,m}}(t) \) is the gas flow of gas storage \( m \) at time \( t \) (It is positive for inflow and negative for outflow); \( u_{\text{gs,m}}(t) \) is the storage price for gas storage \( m \) at time \( t \); \( u_{\text{P2G,k}} \) is the operation cost of P2G \( k \); \( Q_{\text{P2G,k}}(t) \) is the gas flow of P2G \( k \) at time \( t \); \( u_{\text{P2G,k}}(t) \) is the average gas price (In this paper, it is the average price of gas wells).

(2) Minimum the CO2 emissions of the natural-gas system
Min \[ E_{\text{CO}_2} = \sum_{n=1}^{N_w} \sum_{t=1}^{T} E_{\text{wn}}(t) + \sum_{m=1}^{N_s} \sum_{t=1}^{T} E_{\text{gs,m}}(t) - \sum_{k=1}^{N_{\text{P2G}}} \sum_{t=1}^{T} E_{\text{P2G,k}}(t) \] (12)

Where \( E_{\text{CO}_2} \) represents \( \text{CO}_2 \) emissions of the natural-gas system; \( E_{\text{wn}}(t), E_{\text{gs,m}}(t) \) are the \( \text{CO}_2 \) emissions of gas well \( n \), gas storage \( m \) at time \( t \), respectively; \( E_{\text{P2G,k}}(t) \) is the amount of \( \text{CO}_2 \) absorbed by the methanation process of \( \text{P2G,k} \) at time \( t \).

2.2.2 Constraints

(1) Gas flow limits of gas wells

\[ Q_{\text{wn}}^{\text{min}} \leq Q_{\text{wn}}(t) \leq Q_{\text{wn}}^{\text{max}} \] (13)

Where \( Q_{\text{wn}}^{\text{min}}, Q_{\text{wn}}^{\text{max}} \) represent the minimum gas flow and the maximum gas flow of gas well \( n \), respectively.

(2) Gas pressure limits of gas nodes

\[ M_i^{\text{min}} \leq M_i(t) \leq M_i^{\text{max}} \] (14)

Where \( M_i(t) \) represents gas pressure of gas node \( i \) at time \( t \). \( M_i^{\text{min}} \) and \( M_i^{\text{max}} \) are the minimum and maximum gas pressure of gas node \( i \).

(3) Gas flow equation of pipelines

The natural-gas system satisfies the mass conservation law of fluid dynamics and Bernoulli equation in the operation. The relationship between gas flow of pipelines and gas pressure of gas nodes can be modeled as follows [12, 35].

\[ Q_{ij}(t) = \frac{C_{ij} \left( M_i(t)^2 - M_j(t)^2 \right)}{2} \] (15)

\[ Q_{ij}(t) = \frac{Q_{ij}^\text{in}(t) + Q_{ij}^\text{out}(t)}{2} \] (16)

Where \( Q_{ij}(t) \) is the average gas flow of pipeline \( ij \) (Pipeline \( ij \) is the pipeline between gas node \( i \) and gas node \( j \); \( Q_{ij}^\text{in}(t) \) and \( Q_{ij}^\text{out}(t) \) are the injection and withdrawal gas flow of pipeline \( ij \), respectively; \( C_{ij} \) is a constant related to the length, diameter, temperature and compressibility factor of pipeline \( ij \).

(4) Line pack equation

Due to the compressibility of natural gas, the injection gas flow and the withdrawal gas flow of the same pipeline would be different. Some excess natural gas can be stored in the pipelines, which is called line pack. The line pack of pipeline \( ij \) is related to the average pressure and its own parameters of pipelines, which can be modeled as below [12,15].

\[ L_{ij}(t) = \omega_{ij} M_{ij}(t) \] (17)

\[ M_{ij}(t) = \frac{M_i(t) + M_j(t)}{2} \] (18)

\[ L_{ij}(t) = L_{ij}(t-1) + Q_{ij}^\text{in}(t) - Q_{ij}^\text{out}(t) \] (19)
Where $L_{ij}(t)$ is the line pack of pipeline $ij$ at time $t$; $\omega_{ij}$ is a constant related to pipeline parameters, gas constant, compressibility factor, gas density and gas temperature.

(5) Nodal gas flow balance equation

For each gas node, the gas flows into the node must equals the gas flows out of the node.

$$
\sum_{m,i} Q_{in,m}(t) + \sum_{m,o} Q_{out,m}(t) + \sum_{k,i} Q_{P2G,k}(t) - \sum_{j \in Set_{I}(i)} Q_{ij}^{in}(t) + \sum_{j \in Set_{O}(i)} Q_{ij}^{out}(t) - Q_{GT,i}(t) - Q_{L,i}(t) = 0
$$

(20)

Where, the first three items are the gas flow of gas wells, gas storage and P2G located at gas node $i$ at time $t$, respectively; $Q_{GT,i}(t)$ and $Q_{L,i}(t)$ indicate the gas flow injected to gas-fired units and the gas load at gas node $i$ at time $t$, respectively; $Set_{I}(i)$ is the set of pipeline $ij$ which lets gas node $i$ as the input node; $Set_{O}(i)$ is the set of pipeline $ij$ which lets gas node $i$ as the output node.

(6) Gas flow limits and capacity limits of gas storage

$$
Q_{min,m} \leq Q_{gs,m}(t) \leq Q_{max,m}
$$

(21)

$$
V_{min} \leq V_{m}(t) \leq V_{max}
$$

(22)

$$
V_{m}(t) = V_{m}(t-1) + Q_{gs,m}(t)
$$

(23)

Where $Q_{min,m}$ and $Q_{max,m}$ are the minimum and maximum gas flow of gas storage $m$, respectively; $V_{m}(t)$, $V_{min}$, $V_{max}$ are the capacity of gas storage $m$ at time $t$, the minimum and maximum capacity of gas storage $m$, respectively; When the gas is injected to the gas storage, $Q_{gs,m}(t)$ is positive, otherwise is negative.

(7) Compressor

The compressors are used to boost the pressure of the natural-gas network, which can help the natural gas transporting to each gas load. In this paper, the energy consumed by the compressors is calculated by using natural gas flow through the compressors. The consumed gas flow of compressor $r$, $Q_{cr, consume}(t)$, is calculated as presented below [15].

$$
Q_{cr, consume}(t) = \beta_{cr} P_{cr}(t)
$$

(24)

$$
P_{cr}(t) = \frac{Q_{cr}(t)}{\eta_{cr} \cdot \tau \left( \frac{M_{o}(t)}{M_{i}(t)} \right)^{\frac{\alpha}{\alpha - 1}} - 1}
$$

(25)

Where $\beta_{cr}$ is energy conversion coefficient of compressor $r$; $P_{cr}(t)$ is the consumed energy by compressor $r$; $Q_{cr}(t)$ is the gas flow flowing through compressor $r$ at time $t$; $\eta_{cr}$ is the efficiency of compressor $r$; $\tau = (a-1)/a$ and $a$ is variability index of compressors; $M_{o}(t)$ and $M_{i}(t)$ are the pressure of output node and input node of compressor $r$, respectively.

(8) Gas flow limit of P2G

$$
Q_{min,P2G,k} \leq Q_{P2G,k}(t) \leq Q_{max,P2G,k}
$$

(26)

Where $Q_{min,P2G,k}$ and $Q_{max,P2G,k}$ are the minimum and maximum gas flow of P2G k, respectively.

2.3 Gas demand management strategy to coordinate the two energy systems
When the pressure of some gas nodes is higher than the maximum pressure or lower than the minimum pressure, which means the gas demand and the gas supply is not balanced on these gas nodes, then the gas demand management strategy is used. The main idea is to adjust the gas flow of gas turbines to achieve the gas demand balance, which means changing the power output of gas-fired units. Then the power output of units in power system will be adjusted.

2.4 Constraints handling methods

The constraints of power system are handled using the methods presented in [39]. And in this paper, the constraints of natural-gas system are handled by the proposed method as shown below.

2.4.1 Equality constraints handling method

In this paper, the set of non-linear constraints equations (15)-(20) of the natural-gas system are solved by trust region algorithm [43-44] and Levenberg-Marquardt algorithm (L-M) [45-46]. Trust region and L-M methods are both simple and powerful tools for solving systems of nonlinear equations and large-scale optimization problems. They have the advantages of guaranteeing a solution whenever it exists [43-46]. In this paper, trust region method and L-M method are used to solve the gas flow non-linear equations, respectively. And the optimization results are compared in the case studies.

2.4.2 Inequality constraints handling method

For the inequality constraints (13)(14)(21)(22)(26), the gas flow is the minimum when it is lower than the minimum value and the gas flow is the maximum when it is over the maximum value. For the gas storage volume constraint, the effective redundancy method is proposed in this paper. The details of this method are as below.

a) For gas storage $m$ at time $t$;

b) If $V_m(t) \leq V_{m,min}$, calculate $\Delta V = V_{m}^{min} - V_m(t)$;

c) For $ii = 1, t$, calculate the gas flow redundancy of gas storage $m$ at time $ii$. $\Delta Q_{gs}(ii) = \min \{ Q_{gs,m}^m(ii) - Q_{gs,m}(ii), V_{m}^{max} - V_m(ii) \}$; If the gas node where the gas storage $m$ is connected with P2G, $\Delta Q_{P2G}(ii) = Q_{P2G}^{max} - Q_{P2G}(ii)$, the effective redundancy $\Delta Q(ii) = \min(\Delta Q_{gs}(ii), \Delta Q_{P2G}(ii))$; else, $\Delta Q(ii) = Q_{gs,m}(ii)$.

Then, arrange $\Delta Q$ in descending order;

d) According to the descending order, $Q_{P2G}(ii)$ and $Q_{gs,m}(ii)$ are adjusted successively until $V_m(t) \geq V_{m,min}$;

e) Update $V_m(t)$;

f) If $V_m(t) \geq V_{m,max}$, calculate $\Delta V = V_{m}(t) - V_{m}^{max}$;

g) For $ii = 1, t$, calculate the gas flow redundancy of gas storage $m$ at time $ii$. $\Delta Q_{gs}(ii) = \min \{ Q_{gs,m}(ii) - Q_{gs,m}^{min}, V_{gs,m}(ii) - V_{m}^{max} \}$; If the gas node where the gas storage $m$ is connected with P2G, $\Delta Q_{P2G}(ii) = Q_{P2G}(ii) - Q_{P2G}^{max}$, the effective redundancy $\Delta Q(ii) = \min(\Delta Q_{gs}(ii), \Delta Q_{P2G}(ii))$; else, $\Delta Q(ii) = Q_{gs,m}(ii)$.

Then, arrange $\Delta Q$ in descending order;

h) According to the descending order, $Q_{P2G}(ii)$ and $Q_{gs,m}(ii)$ are adjusted successively until $V_m(t) \leq V_{m,max}$;

i) Update $V_m(t)$.

3. Case Studies Application

3.1 Description of case studies

The hybrid electricity-natural gas energy systems shown in Figure 3 is composed by the revised IEEE 39-bus power system[35] and Belgian high-calorific 20-node gas system [3]. The IEEE 39-bus power network has 46 branches, 5 coal-fired units, 3 gas-fired units and 2 wind power units, where the capacity of wind power units accounts for 35% of the total installed capacity of 3903 MW. The Belgian high-calorific 20-node gas system has 24 pipelines, 2 gas wells, 3 gas storages and 2
compressors. The parameters of the power system are from [35,40] and the parameters of natural gas system are from [3]. The revised parameters are shown in Table 1 and Table 2 (inflow of gas storage is positive and outflow of gas storage is negative). Gas pressure limits of gas nodes are given in Table 3. Power demand and gas demand are given in Table 3. In addition, the theoretical predicted wind power output is given in Figure 4. The efficiency of P2G process is taken as 64% [6]. Wind curtailment cost is set as 100 $/MWh [47]. The short-term optimal dispatch for this hybrid energy system is studied to illustrate the behavior of the proposed model, the adopted algorithm and the proposed constraints handling methods in several case studies. These case studies are simulated with a low level of initial line pack (0.5 Mm³). In addition, all the case studies are implemented using MATLAB language programming.

Figure 3. The hybrid electricity-natural gas energy systems

### Table 1. Parameters of power units

<table>
<thead>
<tr>
<th>Power units</th>
<th>$P_{\text{max}}$/MW</th>
<th>$P_{\text{min}}$/MW</th>
<th>Ramp up rate /MW/h</th>
<th>Ramp down rate/MW/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal-fired unit 1</td>
<td>470</td>
<td>150</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Coal-fired unit 2</td>
<td>470</td>
<td>135</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Coal-fired unit 3</td>
<td>340</td>
<td>73</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Coal-fired unit 4</td>
<td>300</td>
<td>60</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Coal-fired unit 5</td>
<td>243</td>
<td>73</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Gas-fired unit 1</td>
<td>260</td>
<td>0</td>
<td>260</td>
<td>260</td>
</tr>
<tr>
<td>Gas-fired unit 2</td>
<td>230</td>
<td>0</td>
<td>230</td>
<td>230</td>
</tr>
<tr>
<td>Gas-fired unit 3</td>
<td>220</td>
<td>0</td>
<td>220</td>
<td>220</td>
</tr>
<tr>
<td>Wind power unit 1</td>
<td>750</td>
<td>0</td>
<td>750</td>
<td>750</td>
</tr>
<tr>
<td>Wind power unit 2</td>
<td>620</td>
<td>0</td>
<td>620</td>
<td>620</td>
</tr>
</tbody>
</table>

### Table 2. Parameters of gas storage

<table>
<thead>
<tr>
<th>Gas storage</th>
<th>Initial capacity/Mm³</th>
<th>Max capacity/Mm³</th>
<th>Min capacity/Mm³</th>
<th>Max gas flow /Mm³/h</th>
<th>Min gas flow /Mm³/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Storage 1</td>
<td>1.5</td>
<td>3.5</td>
<td>0</td>
<td>0.35</td>
<td>-0.20</td>
</tr>
<tr>
<td>Gas Storage 2</td>
<td>2.0</td>
<td>4.5</td>
<td>0</td>
<td>0.45</td>
<td>-0.25</td>
</tr>
<tr>
<td>Gas Storage 3</td>
<td>1.5</td>
<td>3.5</td>
<td>0</td>
<td>0.35</td>
<td>-0.25</td>
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</tbody>
</table>

### Table 3. Gas pressure limits of gas nodes
Table 4. Power demand and gas demand

<table>
<thead>
<tr>
<th>Time/h</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power demand/MW/h</td>
<td>1272</td>
<td>1188</td>
<td>1104</td>
<td>960</td>
<td>1080</td>
<td>1320</td>
<td>1476</td>
<td>1584</td>
<td>1740</td>
<td>1776</td>
<td>1800</td>
<td>1860</td>
</tr>
<tr>
<td>Gas demand/ Mm³/h</td>
<td>1.03</td>
<td>0.97</td>
<td>0.92</td>
<td>0.98</td>
<td>0.99</td>
<td>1.03</td>
<td>1.23</td>
<td>1.45</td>
<td>1.79</td>
<td>1.83</td>
<td>1.74</td>
<td>1.61</td>
</tr>
</tbody>
</table>

Figure 4. Predicted output of wind power units

3.2 Analysis of simulation results

The Newton-Raphson method is used to obtain the power flow. Trust region method and L-M method are used to solve the non-linear equations to obtain the gas flow in natural-gas system, respectively. Furthermore, MOBPSO [39-42] is used to optimize the multi-objective dispatch problem of hybrid electricity-natural gas energy systems based on the established models (1)(2)(3)(7)(12), the proposed flow chart (Figure 2.) and the proposed constraints handling methods. The optimization results are shown in Table 5 and Table 6. All the constraints are satisfied. The comparisons of power output and gas flow among different case studies are given in Figure 5 and Figure 6, respectively. Moreover, it can be found the different performance of trust region method and L-M method from Figure 7 and Table 6. The wind power absorbed by P2G and the gas flow of P2G are shown in Figure 8. The volume of gas storages is given in Figure 9. And the gas pressure of each gas node can be found in Appendix A.

From the obtained results, it can be seen that power output, gas flow of gas wells, gas flow of P2G, gas flow of gas storages, volume of gas storages and gas pressure of gas nodes all satisfy their
respective upper and lower bound constraints. Besides, the nodal gas flow balance equation is satisfied. Moreover, power demand and power supply are balanced which can be drawn from the calculated load loss rate \( L_p = 6.37 \times 10^{-18} \). Then the above results show that all the constraints are satisfied using the proposed constraints handling methods.

**Table 5. Optimization results of the power system**

<table>
<thead>
<tr>
<th>Fuel cost (M$)</th>
<th>SO(_x) emission(ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without P2G</td>
<td>1.080</td>
</tr>
<tr>
<td>With P2G</td>
<td>1.084</td>
</tr>
</tbody>
</table>

**Table 6. Optimization results of the natural-gas system**

<table>
<thead>
<tr>
<th>Cost of natural-gas/m$</th>
<th>CO(_2) emission/10(^4) ton</th>
<th>Rate of abandoned wind power</th>
<th>Operation cost of P2G/m$</th>
<th>Absorbed CO(_2) by the methanation process/10(^4) ton</th>
<th>Increased wind power by P2G/MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without P2G Trust Region</td>
<td>0.741</td>
<td>5.791</td>
<td>24.85%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>L-M</td>
<td>0.695</td>
<td>5.790</td>
<td>24.85%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>With P2G Trust Region</td>
<td>0.732</td>
<td>5.727</td>
<td>6.71%</td>
<td>0.106</td>
<td>0.056</td>
</tr>
<tr>
<td>L-M</td>
<td>0.685</td>
<td>5.491</td>
<td>4.04%</td>
<td>0.122</td>
<td>0.064</td>
</tr>
</tbody>
</table>

**Figure 5.** Comparison of power output without P2G and with P2G

### 3.2.1 Effects of P2G on the power system

(1) From Table 5 and Figure 5, it can be seen that the fuel cost of power system with P2G is a little higher than that without P2G. At the hour 20, owing to the gas injection from P2G, the pipeline pressure is higher than the maximum value, so the ‘gas demand management strategy’ is used and it needs to increase the gas demand by increasing the output of gas-fired units connected with gas.
node 5 and 14. Then, to guarantee the power load balance, the output of coal-fired units would be reduced. Because the fuel cost of gas-fired units is higher than that of coal-fired units and the SO\textsubscript{x} emissions of gas-fired units are lower than that of coal-fired units, it leads to increase of fuel cost and decline of SO\textsubscript{x} emissions. And the SO\textsubscript{x} emissions are reduced by 0.254 ton. In addition, from Figure 8, most abandoned wind power can be absorbed by P2G. During hours 3-5, P2G works at its maximum value when the abandoned wind power is over the maximum capacity of P2G. Owing to the P2G, the wind power output is much smoother and so is the output of coal-fired units, which is propitious to the stability and reliability of the power system.

(2) From Table 6 and Figure 7(a), it is obvious that the rate of abandoned wind power is declined from 24.85% to 6.71% (trust region) and from 24.85% to 4.04% (L-M), respectively; The wind power output is increased by 5321.66MWh (trust region) and 6104.48MWh (L-M), respectively.

![Figure 6. Comparison of gas flow without P2G and with P2G](image)

![Figure 7. Results comparison of trust region method and L-M method](image)

3.2.2 Effects of P2G on the natural-gas system

From Figure 6 and Figure 9, it’s obvious that the gas flow of gas wells and gas storages is lower when P2G is considered. Besides, the volume of gas storages with P2G is much larger than that
without P2G. This is because the economic, clean and low carbon energy converted by P2G from wind power has the priority of use compared with that from natural gas network, which creates considerable economic and environmental benefits for the integrated energy systems. The cost benefit of P2G is evaluated in terms of the natural gas cost which it displaces. From Table 6, it can be seen the gas cost is reduced by 9000 $ (trust region) and 10000$ (L-M), respectively; Moreover, the environmental benefit of P2G in terms of CO\textsubscript{2} reduction and CO\textsubscript{2} absorbed in the P2G methanation process is measured. The total CO\textsubscript{2} emissions are declined by 1200 ton (trust region) and 3630 ton (L-M), respectively.

Figure 8. Wind power absorbed by P2G and the gas flow of P2G

Figure 9. Volume of gas storages without P2G and with P2G
3.2.3 Total cost reduction of the hybrid energy systems

The total cost of the hybrid electricity-natural gas energy systems including the wind power curtailment cost is reduced by 5.372×10^5$ (trust region) and 6.165×10^5$ (L-M), which can be seen from Figure 7(b).

It can be concluded that the proposed model, the proposed constraints handling methods are effective and the feasibility of MOBHPSO algorithm for solving the multi-objective optimal dispatch problem of the hybrid electricity-natural gas energy systems is indicated. Moreover, the trust region method and L-M method are effective to solve the nonlinear gas flow problem. And it also can be seen that the results obtained from L-M method is much better than those obtained from trust region method.

4. Conclusion

This paper presented a multi-objective optimal dispatch model of the hybrid electricity-natural gas energy systems coupled by P2G and gas turbines, in order to achieve the maximum of low-carbon economic environmental benefits. The proposed model provides not only enhanced flexibility as it easily handles bidirectional energy flow and guarantees global optimality, but also considers the compressibility of gas, line pack of pipelines among other complicated system characteristics. The nonlinear and non-convex functions of gas flow model are addressed by trust region method and L-M method. And the L-M method has much better performance which can be drawn from the simulation results. Moreover, the case studies simulation results show the feasibility of MOBHPSO algorithm for solving the multi-objective optimal dispatch problem of the hybrid electricity-natural gas energy systems and the effectiveness of proposed constraints handling methods. The obtained results also illustrate that P2G can significantly benefit the operation of both power system and natural gas system in smoothing power output, cutting down gas cost, reducing CO2 emissions and SOx emissions as well as avoiding wind curtailment. More specifically, the gas cost is cut down up to 10000 $, the total CO2 emissions are declined up to 3630 ton and the SOx emissions are reduced by 0.254 ton as well as the wind power curtailment is decreased up to 6104.48 MWh with the rate of abandoned wind power declined from 24.85% to 4.04%. Besides, the total cost including wind power curtailment cost is reduced up to 6.165×10^5$.

Author Contributions: Dr. Jing Liu proposed the optimization model and algorithms, carried out case studies, completed the entire analysis and wrote this paper; Prof. Gareth Harrison gave essential and important advice on the model of natural-gas system; Dr. Wei Sun gave some important suggestions on the calculation of gas flow and revised this paper.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

<table>
<thead>
<tr>
<th>Table A1. Gas pressure of each gas node</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node No.</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Hour 1</td>
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<tr>
<td>Hour 2</td>
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<tr>
<td>Hour 3</td>
</tr>
<tr>
<td>Hour 4</td>
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<tr>
<td>Hour 5</td>
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<tr>
<td>Hour 6</td>
</tr>
<tr>
<td>Hour 7</td>
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<tr>
<td>Hour 8</td>
</tr>
<tr>
<td>Node No.</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Hour 1</td>
</tr>
<tr>
<td>Hour 2</td>
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<td>Hour 3</td>
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<td>Hour 4</td>
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<td>Hour 23</td>
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<tr>
<td>Hour 24</td>
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