Economic Impact of PTG in Integrated Electricity-Gas System with High Wind Penetration

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- Multi-state wind generation model
- Optimization formulation of IEGS
- Case study

1 Background

Generation from gas

Power to gas technology

Consuming surplus wind using PTG

Generation from gas

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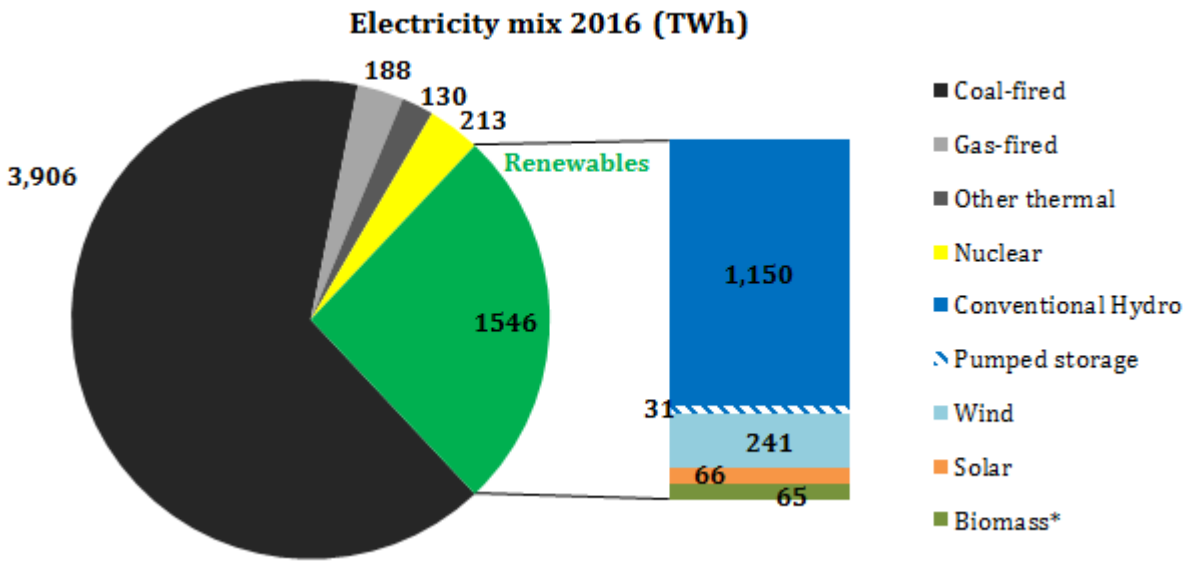
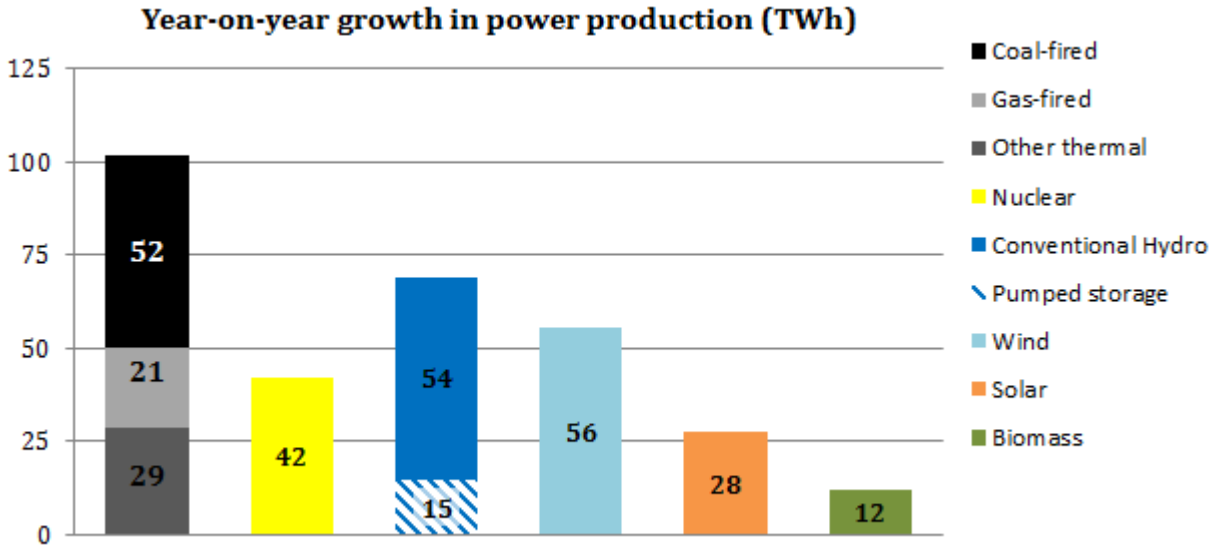
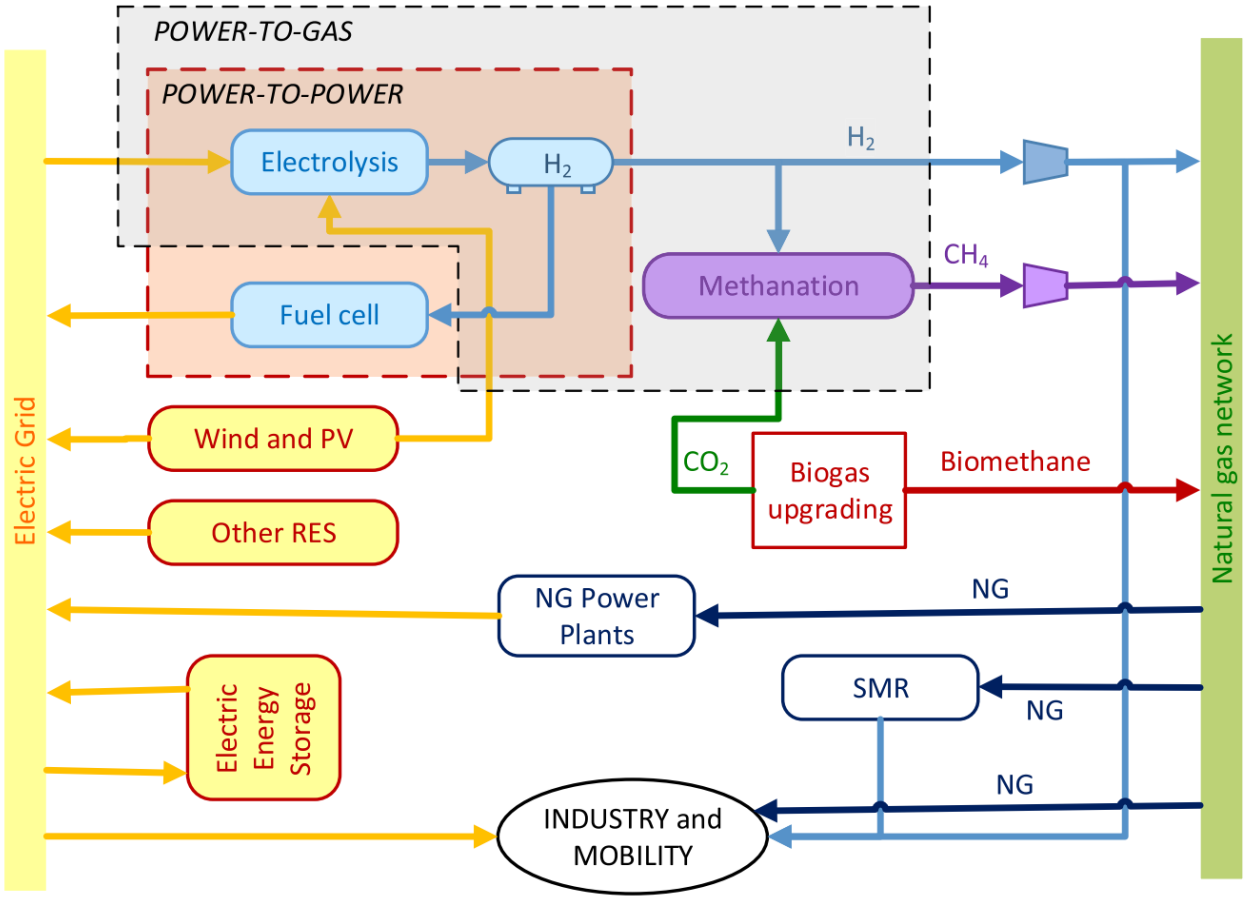




Until 2016, the generation from natural gas reaches to **188.1 TWh** in China, with year-on-year growth of **12.7%**

Consuming surplus wind using PTG



electrolysis $2H_2O \xrightarrow{\text{电解}} 2H_2O+O_2$

methanation $CO_2+4H_2 \rightarrow CH_4+2H_2O$

$$G^{ptg} = \phi P^{ptg} e_a^{ptg} / HHV$$

$$HHV = 1.026 MBtu/kcf \qquad \phi = 3.4 MBtu/MWh$$

2 Multi-state wind generation model

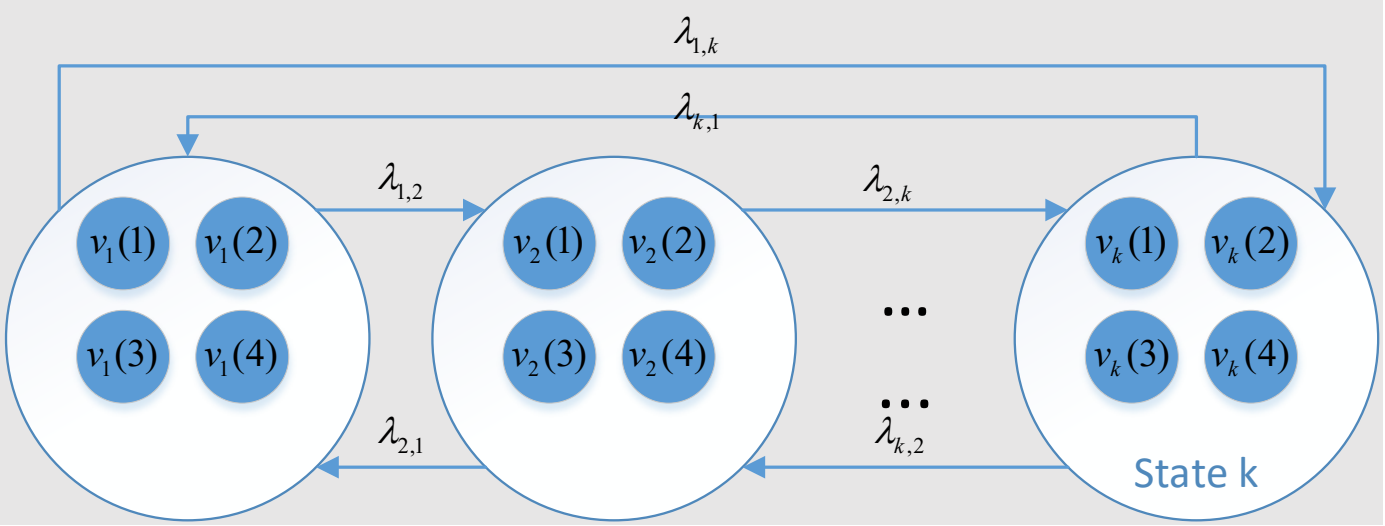
Modeling multi-state wind generation

Sampling wind generation sequence

Modeling multi-state wind generation

1. Cluster wind speed into several state manually

2. Calculate state transition rate based on historical data



Multi-state wind probability transition model

3. Calculate power generation for each wind turbine

$$P_w = \begin{cases} 0 & 0 < v < v_{ci} \\ 0.5 C_p \rho_0 \pi r^2 v^3 & v_{ci} < v < v_r \\ P_r & v_r < v < v_{co} \\ 0 & v > v_{co} \end{cases}$$

Sampling wind generation sequence

4 Calculate the duration of current state

The duration of state k can be calculated with following formulation

$$D_k = -\ln U / \sum_{i=1}^{m} \lambda_i$$

5 Determine the next state

the probability of entering each state can be calculated as: $P_{k'} = \lambda_{k'} / \sum_{i=1}^{m} \lambda_i$

If $\sum_{i=1}^{k'-1} P_i < U \le \sum_{i=1}^{k'} P_i, 1 \le k' \le m$

then the next state will be k'

6 Merge the generation of wind turbines

The loop will continue until the preset simulation period is reached. Above those, we consider at maximum 5th-ordered failure.

3 Optimization formulation of IEGS and proposed indices

Gas system equations

Joint optimization formulation

Proposed indices

Gas system equations

- The natural gas at each bus will follow the mass conservation

$$P_{S,i}^{g} - P_{D,i}^{g} + P_{PTG,i}^{g} - P_{GFU,i}^{g} = \sum_{j \in nl_i^g} f_{ij}^{g}$$

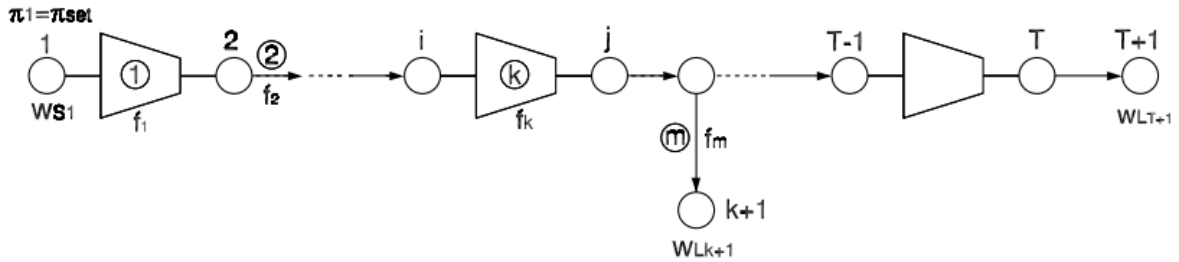
- Weymouth power flow equation

$$f_{ij}^{g} = K_{ij} S_{ij} \sqrt{S_{ij}(p_i^{\,2} - p_j^{\,2})}$$

$$K_{ij} = 3.0996 \times 10^{-7} [2\log(3.7 D_{ij} / \varepsilon)] \sqrt{D_{ij}^{5} / zT\delta L_{ij}}$$

- Dirichlet function

$$S_{ij} = \begin{cases} 1, p_i \geq p_j \\ -1, p_i < p_j \end{cases}$$



Structure of gas system

- Gas-fired unit

$$P_{GFU,i}^{g} = K_{2,i} P_{GFU,i}^{e\ 2} + K_{1,i} P_{GFU,i}^{e} + K_{0,i}$$

- Power to gas

$$P_{PTG,i}^{e} = \eta_i H_g P_{PTG,i}^{g}$$

efficiency of PTG is usually considered as 0.55~0.75

Joint optimization formulation

- minimize the comprehensive operation cost

$$obj: \min\ C_{IEGS} = GC_{TG} - RG$$
$$= \sum_{i=1}^{i=nb^e} \left(\sum_{j=1}^{j=n_{i,TG}} (a_{i,j} + b_{i,j} P^e_{G,i,j} + c_{i,j} {P^e_{G,i,j}}^2) - \rho_i \sum_{j=1}^{j=n_{i,PTG}} P^g_{PTG,i,j} \right)$$

- control variables

$$CV = [P^e_{TG}, P^e_{GFU}, P^g_{PTG}]$$

- Flow equations in power system

$$P^e_{G,i} - P^e_{D,i} + P^e_{GFU,i} - P^e_{PTG,i} + \mathrm{j}(\mathrm{Q}_{G,i} - Q_{D,i}) = \sum_{j \in nl^e_i} {f_{ij}}^e$$

$${f_{ij}}^e = V_i V_j ((G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) + j(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}))$$

- Constrains in power system

$$\underline{P^e_{G,i,j}} \le P^e_{G,i,j} \le \overline{P^e_{G,i,j}} \qquad \underline{Q^e_{G,i,j}} \le Q^e_{G,i,j} \le \overline{Q^e_{G,i,j}}$$

$$\underline{P^e_{GFU,i,j}} \le P^e_{GFU,i,j} \le \overline{P^e_{GFU,i,j}} \qquad \underline{Q^e_{GFU,i,j}} \le Q^e_{GFU,i,j} \le \overline{Q^e_{GFU,i,j}}$$

$$\underline{f^e_{ij}} \le f^e_{ij} \le \overline{f^e_{ij}}$$

- Constrains in gas system

$$\underline{f^g_{ij}} \le f^g_{ij} \le \overline{f^g_{ij}}$$

$$\underline{P^g_{S,i,j}} \le P^g_{S,i,j} \le \overline{P^g_{S,i,j}}$$

$$\underline{P^g_{PTG,i,j}} \le P^g_{PTG,i,j} \le \overline{P^g_{PTG,i,j}}$$

Proposed indices

The goals

(a) contribute to the consumption of surplus wind energy;
(b) improve efficiency, reduce operation cost for market participants or Independent System Operator (ISO);
(c) interact to achieve better resilience and robustness.

Expectations

$$E(X)=(\sum_{i=1}^{n_{st}}\sum_{j=1}^{n_{tf,i}}X(i,j)*D(i,j)/\sum_{j=1}^{n_{tf}}D(i,j))/n_{st}$$

- Wind consumption rate

$$WCR=E((\sum_{i=1}^{i=nb^e}\sum_{j=1}^{j=n_{wt,i}}P^e_{G_{wf},i,j})/P^e_{wc})$$

- Gas supplied by PTGs rate

$$S^g=E((\sum_{i=1}^{i=nb^e}\sum_{j=1}^{j=n_{PTG,i}}P^g_{PTG,i,j})/P^g_{total})$$

- Energy exchange rate

$$S=S^g+S^e \qquad S^e=E((\sum_{i=1}^{i=nb^e}\sum_{j=1}^{j=n_{GFU,i}}P^e_{GFU,i,j})/P^e_{total})$$

4 Case study

Brief on test system

Time-varying indices

Statistical indices

Brief on test system

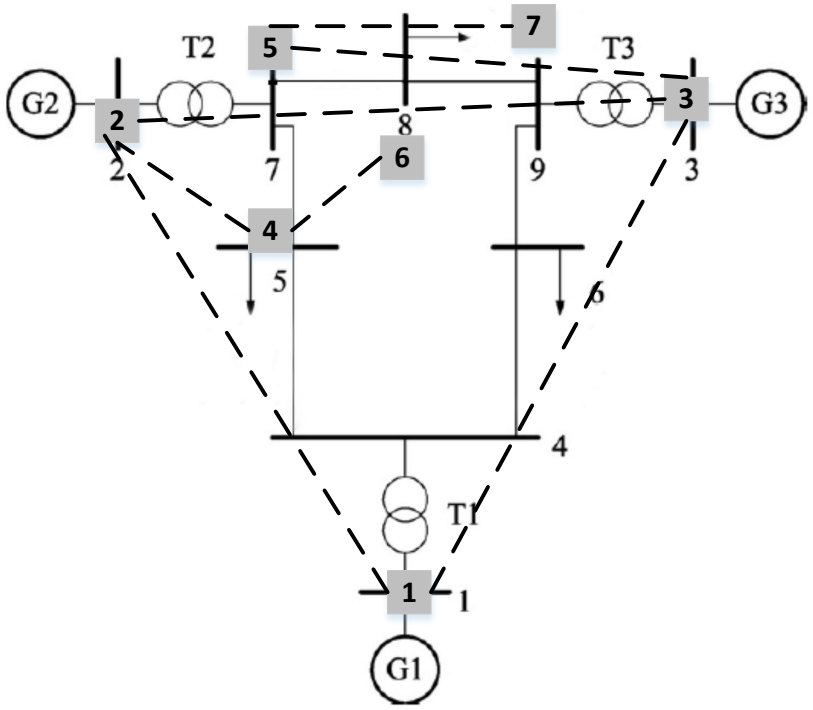


Diagram of IEGS test case

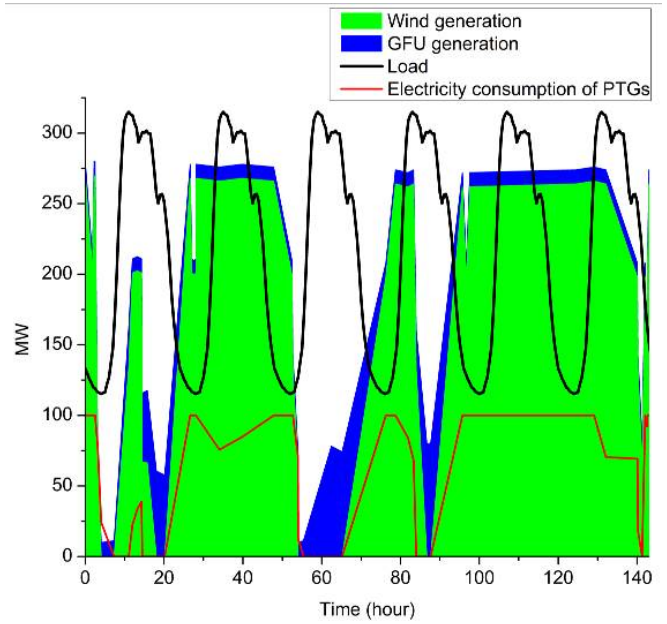
Original system

- IEEE 9-bus power system case
- 7-bus gas transmission system

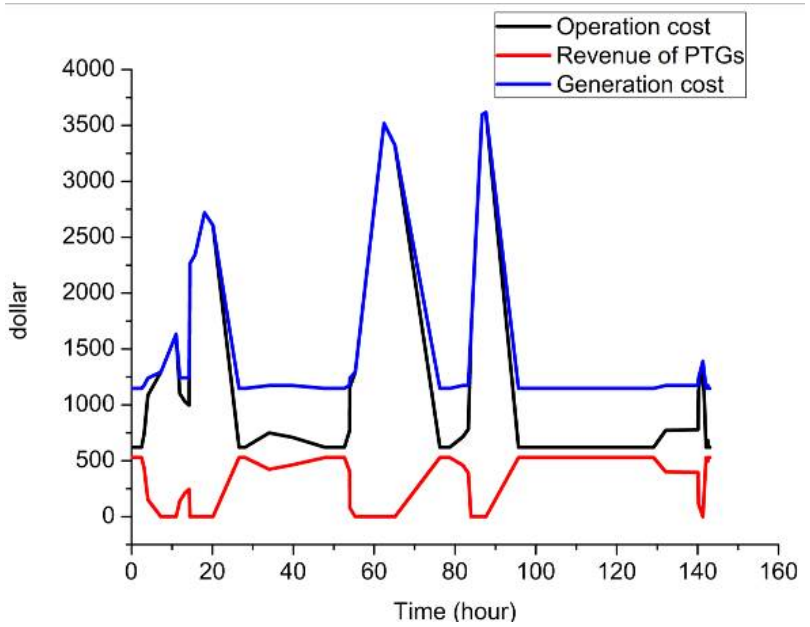
Modifications

- the two systems are coupled by two PTG facilities and one gas fired unit, located in electricity bus 7, bus 9, and bus 1, respectively.
- In electricity system, we replaced 270 MW generator at bus 3 with a wind farm containing 135 2 MW wind turbines. The penetration rate of wind capacity is 32.93%.
- Moreover, the GFU at bus 1 takes the place of the traditional generator with the same capacity.

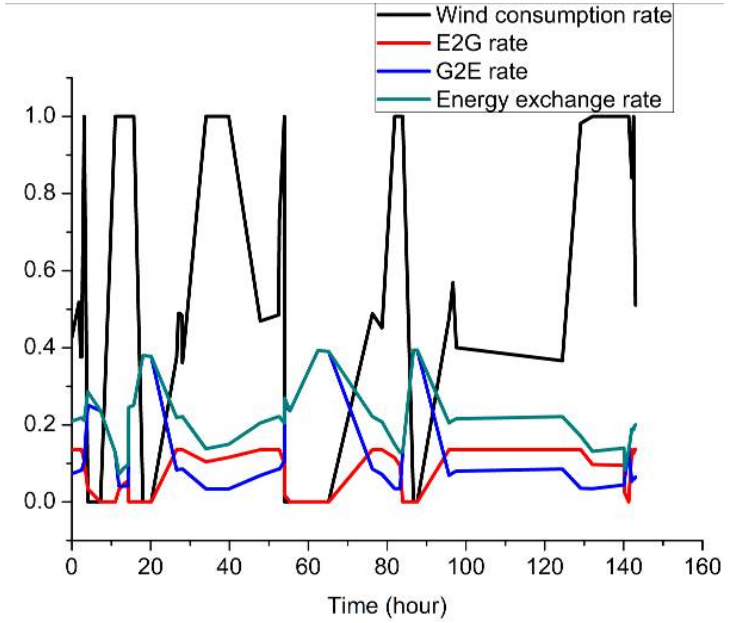
Time-varying indices



Generation and load profile of test case



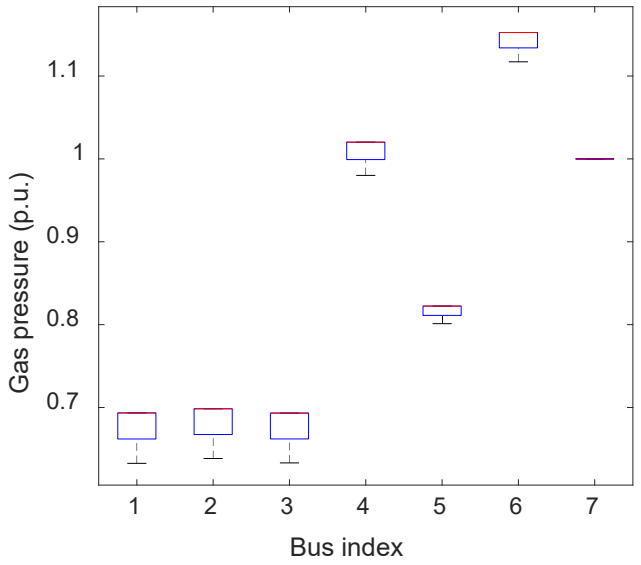
Operating cost composition



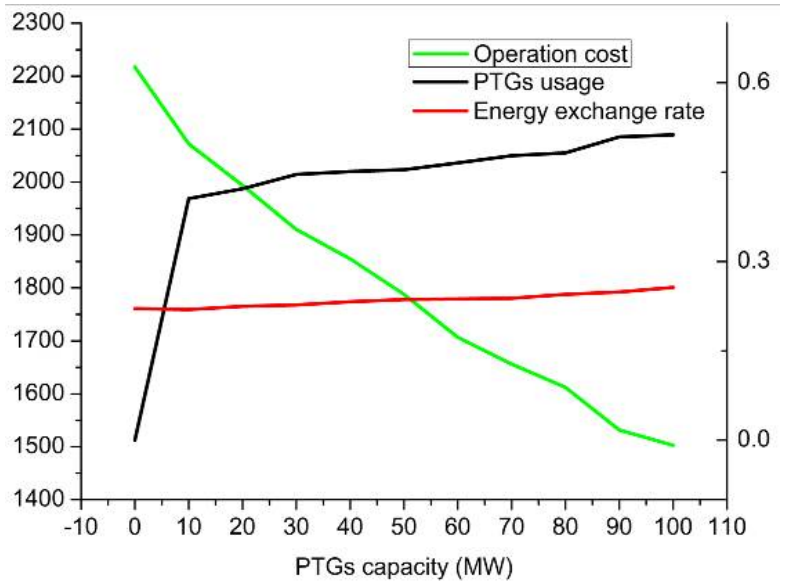
Wind consumption and energy exchange rate

- The electricity consumption of PTGs and generation of GFUs shows strong correlation with wind energy and load level.
- wind shortage comes with an increase of operation cost. However, the revenue of gas selling to the gas system makes certain compensation.
- The energy exchange rate can be utilized to estimate the activity level of energy exchange devices.

Statistical indices



Nodal pressure in natural gas system



Wind consumption and energy exchange rate

Indices	With two 50MW PTGs	Without PTG
Wind generation	138.6	138.9
Electricity consumption of PTGs	51.26	0
GFU generation	27.38	49.62
Operation cost	1502	2217
Revenue of PTGs	277.3	0
Generation cost	1780	2217
Wind consumption rate	45.60%	45.49%
E2G rate	6.99%	0
G2E rate	18.63%	22.10%
Energy exchange rate	25.62%	22.10%
Variance of nodal gas pressure	0.0395	0.0415

comparison between scenarios

under the same natural condition, investment on PTG facilities can remarkably reduce the operation cost, by **32.25%**. On the other hand, it also increases the energy exchange rate by **3.52%**, which will improve the system resilience when energy supply shortage or component fault occurs.

Thanks!

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