Economic Impact of Power to Gas in Integrated Electricity and Gas System with High Wind Penetration

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***Abstract*—Electricity and gas network have a tendency to be integrated in system planning and energy dispatch to achieve higher efficiency and complementarity. Power to gas (PTG) is a recently developed energy conversion technique. It consumes electricity and transfer raw material into gas, which can be injected to the gas distribution system. Along with gas-fired units (GFUs), it gives a bidirectional interaction between gas and electricity system. This raised new challenges for operation of integrated electricity-gas system (IEGS), especially when installed with a large portion of renewable energy generation. This paper proposed an economic dispatch model of IEGS with bidirectional energy flow. Wind generations were multi-state modeled, and simulated utilizing time-sequential Monte-Carlo simulation technique, which is novel in IEGS evaluation. An optimal power flow in IEGS was calculated. Multi-dimensional indices are defined, and calculated to evaluate the impact of PTGs on IEGS under an IEEE and gas test system.**

***Index Terms*—Energy exchange; integrated electricity and gas system; power to gas; time-sequential Monte-Carlo simulation; wind generation.**

I. Introduction

With the growing concern for the environmental and sustainable development, multiple kinds of energy transmission and distribution system are co-planned and co-operated to achieve better efficiency and robustness [1], [2]. It is usually claimed as integrated energy system (IES), with multiple energy carriers of electricity, gas, heat, cold, etc. [3]. Among those energy form, electricity and natural gas are strongly coupled due to the widely used gas-fired units (GFUs). Until 2016, the generation from natural gas reaches to 188.1 *TWh* in China, with year-on-year growth of 12.7% [4]. Therefore, the joint modeling and cooperation strategy of integrated electricity and gas system (IEGS) has become a rising research focus.

Power to gas (PTG) is a recently developed device to transfer the raw material, such as water, CO , CO_2 into CH_4 . This technique contains two sub-process, water electrolysis and methanation, where electricity consumption is crucially required [5]. The produced gas is compatible with the existing gas distribution system, and can be injected to gas consumption or storage facilities for further use [6]. Technical and economic assessments, as well as the practical demonstration projects, have been conducted in several countries like Italy and German [7], [8].

Recently, the energy flow issues of IEGS has been well addressed through constructive researches [9]-[12]. Reference [9], [10] proposed an energy integration model "energy hub", where the connection of various energy carriers can be abstracted in a universal form. However, it only represents energy carriers at a single bus, nor have the possible time lag and transient characteristic of the dynamic process for each energy form been considered. Reference [11] made a thorough study about the optimization model of integrated gas and electricity transmission network and reference [12] has considered the discrepant time constant of the gas and electricity dynamic process in short-term simulation, by taking gas traveling velocity and compressibility into account. Based on the knowledge of optimal flow of IEGS and PTG mathematical model [13], application of PTG has been studied in economical operation and equipment investment [14]. Reference [15] sets PTGs as an influential factor in IEGS co-planning to optimize system efficiency and robustness. Reference [16] proposed a scheme on interaction in IEGS to diminish both operation cost and carbon emission, under the vision of large-scale installation of PTG facilities. In addition, PTGs can be utilized to suppress the fluctuation and intermittence of renewable energy, such as wind power, by converting surplus electricity into gas storage [17]. In the reference [18], the pipeline storage is considered for multiple time period due to the compressibility of natural gas, in receding optimization of wind consumption. Despite the abundant models of IEGS, seldom literature has deliberated on the stochastic behavior of wind generation, nor has the probability model of wind been utilized in IEGS evaluation, which is essential in both operational and long-term time scale.

The paper evaluated the impact on IEGS with PTG facilities, considering the stochastic behavior of wind in the electricity supply side. It was organized as follows. In section

The research is supported by the State Grid Corporation of China: Research on key technologies in supply and demand side interaction in electricity market (5211JY160010), the National Natural Science Foundation of China under Grant 51577167 and 51611130197.

978-1-5386-4291-7/18/$31.00 ©2018 IEEE

2, the non-linear model of IEGS was interpreted, as well as the coupling components, such as the GFUs and PTGs. In section 3, the wind probability transition model was established based on Markov process and simulated time sequentially. In section 4, the optimization model of IEGS was specified, and several indices were proposed. The optimal strategy and evaluation were illustrated and verified using IEEE 9-buses case and 7-buses gas transmission test system in section 5, and conclusions were drawn in section 6.

II. MATHEMATICAL MODEL OF IEGS

A. Natural gas transmission system

Topologically, Natural gas transmission system consists of buses and branches, where physically a bus can represent a gas well, a gas consumer aggregation or gas tank. Branches represent the gas pipelines or compressors. The natural gas at each bus will follow the mass conservation:

$$P_{S,i}^{g} - P_{D,i}^{g} + P_{PTG,i}^{g} - P_{GFU,i}^{g} = \sum_{j \in nl_i^g} f_{ij}^{g} \tag{1}$$

Where f_{ij}^{g} is the mass flow of natural gas from node i to node j . Assumption is usually made that the temperature of the gas remains the same from the beginning to the end of the pipeline. $P_{S,i}^{g}, P_{D,i}^{g}, P_{PTG,i}^{g}, P_{GFU,i}^{g}$ represent the gas supply, gas demand, gas production of PTGs, gas consumption of GFUs at bus i , respectively. nl_i^g is the set of pipelines that are connected to bus i in gas transmission system. The gas flow f_{ij}^{g} can be calculated with

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

This is called as Weymouth power flow equation. It is suitable for gas transmission system, where the diameters of pipelines are relatively large and pressures are high [11]. S_{ij} is the Dirichlet function given by

$$S_{ij} = \begin{cases} 1, p_i \geq p_j \\ -1, p_i < p_j \end{cases} \tag{3}$$

Where p_i and p_j are the pressures of natural gas in bus i and bus j , respectively. K_{ij} is a constant value to characterize the gas pipeline from bus i to bus j , which usually takes experience value from [19]:

$$K_{ij} = 3.0996 \times 10^{-7} [2\log(3.7 D_{ij} / \varepsilon)] \sqrt{D_{ij}^5 / zT\delta L_{ij}} \tag{4}$$

Where D is the diameter of pipeline. ε is the absolute rugosity of natural gas pipeline. z, T, δ, L represent the natural gas compressibility factor, temperature, density of natural gas relative to air, length of the pipeline, respectively.

In the electricity network, the nodal conservation can be expressed in the form of

$$P_{G,i}^{e} - P_{D,i}^{e} + P_{GFU,i}^{e} - P_{PTG,i}^{e} + \mathrm{j}(\mathrm{Q}_{G,i} - Q_{D,i}) = \sum_{j \in nl_i^e} f_{ij}^{\,e} \tag{5}$$

Where $P_{G,i}^{e}, P_{D,i}^{e}, P_{GFU,i}^{e}, P_{PTG,i}^{e}$ is the electricity generation from non-gas sourced units, electricity demand, electricity generation of GFUs, electricity consumption of PTGs at bus i ,respectively. Electricity power flow is calculated using AC model:

$$f_{ij}^{\,e} = V_i V_j ((G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) + j(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij})) \tag{6}$$

Where Q_G and Q_D represent the reactive power of generator and load. V and θ represent the aptitude and phase angle of voltage. G and B represent nodal conductivity and susceptance, respectively.

B. Gas-fired units

Gas-fired unit is one of the important joint between the electricity system and gas system. The power output and the natural gas supply is formulated as:

$$P_{GFU,i}^{g} = K_{2,i} {P_{GFU,i}^{e}}^{2} + K_{1,i} P_{GFU,i}^{e} + K_{0,i} \tag{7}$$

Where parameters K_0, K_1, K_2 is determined by the specific operation condition of GFUs. We assume that $K_2 = 0, K_1 = 0.005, K_3 = 0; ((Mm^3/h)/MW)$ [20].

C. PTG facilities

PTGs consume electricity, produce gas and inject into gas system. The calculation formulation can be simply expressed as follow [15]:

$$P_{PTG,i}^{e} = \eta_i H_g P_{PTG,i}^{g} \tag{8}$$

Where η_i is the efficiency of PTG, which is usually considered as 0.55~0.75. $H_g = 39MW/(m^3/s)$ is the heat value of natural gas.

III. MULTI-STATE WIND GENERATION PROBABILITY TRANSITION MODEL

The power output of a wind farm is determined by the number of wind turbines and the generation of each wind turbine. The velocity of wind has coloration in location, which in this paper, is regarded the same for each wind turbine in the same wind farm. The generation of each wind turbine is a piece-wise function of wind velocity [21]:

$$P_w = \begin{cases} 0 & 0 < v < v_{ci} \\ 0.5 C_p \rho_0 \pi r^2 v^3 & v_{ci} < v < v_r \\ P_r & v_r < v < v_{co} \\ 0 & v > v_{co} \end{cases} \tag{9}$$

Where C_p is the power factor of wind turbine, ρ_0 is the density of air, r is the length of blade, v represents the wind speed, and P_r is the rated power. v_{ci} , v_r and v_{co} are the cut-in, rated and cut-out speed, respectively.

The wind speed is usually modeled as a time-varying value in other papers, as the wind generation simulated in time-domain. However, it can only simulate as a typical period, and the fluctuation of wind is not technically considered, for the statistic parameters, such as the expectation value and risk is not reflected during the simulation. In this paper, we modeled wind speed as a multi-state probability transition model based on Markov chain. Suppose the wind speed $v(k_s T_s)$ is collected by meters with time interval of T_s, where $k_s = 1,2,3,...$. And the probability distribution $f(v)$ will be determined accordingly, where v take values from range of $v(k_s T_s)$. We manually clustered v into k sub-states $\{v_1, v_2, ..., v_k\}$, where every sub-states contains sub-range $v(k_s T_s)$. For example, $v_1 = \{v_1(1), v_1(2), ..., v(n_1)\} \in (\underline{v_1}, \overline{v_1}]$ .That is to say, the probability distribution of wind speed has been discretized and divided into multiple states. The state space $S_{wind} = \{S_1, S_2, ..., S_k\}$, and the transition rate from state i to state j is defined as λ_{ij} , as show in the Fig. 1

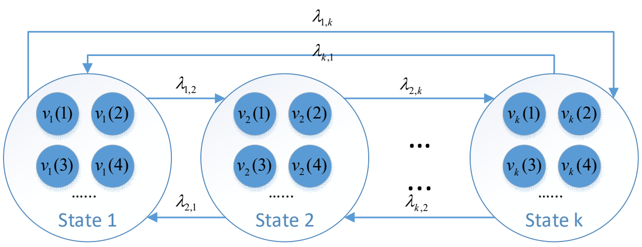

Figure 1. Multi-state wind probability transition model

The time-sequential Monte Carlo simulation was performed according to the probability transaction model. Suppose in the initial state, wind speed is at v_r , and all wind turbines were operating at the rate power. The duration of state k can be calculated with following formulation [22]:

$$D_k = -\ln U / \sum_{i=1}^{m} \lambda_i \tag{10}$$

Where U represents a random number subjected to uniform distribution in [0,1] , m represents the number of states which depart from state k . At the end of each state k , the components will enter another state k' .the probability of entering each state can be calculated as

$$P_{k'} = \lambda_{k'} / \sum_{i=1}^{m} \lambda_i \tag{11}$$

Obviously, $\sum_{k'=1}^{m} P_{k'} = 1$. U' is a random number in [0,1] subjected to uniform distribution . 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' .

The loop will continue until the preset simulation period is reached. Above those, we consider at maximum 5th-ordered failure. The failure rate and repair rate for wind turbine is λ_{wt} and μ_{wt} , respectively.

IV. OPTIMIZATION MODEL AND EVALUATION INDICES OF IEGS

A. optimization model

In IEGS containing PTGs and GFUs, the goal of optimization is to minimize the comprehensive operation cost of IEGS.

$$obj: \min\ C_{IEGS} = GC_{TG} - RG$$
$$= \sum_{i=1}^{i=nb^e} \Big(\sum_{j=1}^{j=n_{i,TG}} (a_{i,j} + b_{i,j} P^e_{G,i,j} + c_{i,j} {P^e_{G,i,j}}^2) - \rho_i \sum_{j=1}^{j=n_{i,PTG}} P^g_{PTG,i,j} \Big) \tag{12}$$

where C_{IEGS} is total cost of IEGS, and GC_{TG} , RG is the generation cost of traditional units and the revenue of natural gas production of PTGs, respectively. $n_{i,TG}$ and $n_{i,PTG}$ are the number of traditional units and PTGs in bus i . ρ_i is the nodal gas price at bus i .

The control variables in the optimization of IEGS are represented by the matrix $CV = [P^e_{TG}, P^e_{GFU}, P^g_{PTG}]$, where P^e_{TG} represents the vector of traditional generators power output. The constrains of electricity system, including active power and reactive power limitations of non-gas consuming generators (13), (14) and GFUs (15), (16), limitations of electricity branches (17) are listed as follows:

$$\underline{P^e_{G,i,j}} \le P^e_{G,i,j} \le \overline{P^e_{G,i,j}} \tag{13}$$

$$\underline{Q^e_{G,i,j}} \le Q^e_{G,i,j} \le \overline{Q^e_{G,i,j}} \tag{14}$$

$$\underline{P^e_{GFU,i,j}} \le P^e_{GFU,i,j} \le \overline{P^e_{GFU,i,j}} \tag{15}$$

$$\underline{Q^e_{GFU,i,j}} \le Q^e_{GFU,i,j} \le \overline{Q^e_{GFU,i,j}} \tag{16}$$

$$\underline{f^e_{ij}} \le f^e_{ij} \le \overline{f^e_{ij}} \tag{17}$$

Where $\underline{P^e_{G,i}}$, $\overline{P^e_{G,i}}$ represent the low boundary and up boundary of generator j at bus i , and similarly for reactive power output Q .

In the gas system, the constrains are similar, including natural gas sources upper and lower bounds (18), limitation of gas pipelines (19), limitations of PTGs (20):

$$\underline{P^g_{S,i,j}} \le P^g_{S,i,j} \le \overline{P^g_{S,i,j}} \tag{18}$$

$$\underline{f^g_{ij}} \le f^g_{ij} \le \overline{f^g_{ij}} \tag{19}$$

$$\underline{P^g_{PTG,i,j}} \le P^g_{PTG,i,j} \le \overline{P^g_{PTG,i,j}} \tag{20}$$

B. evaluation indices

Beside the objective function in the optimization model, other indices are required to evaluate the operating condition of IEGS comprehensively. The goals of investment on PTG facilities are, (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.

Based on the time-sequential Monte Carlo simulation, $E(X)$ means the expectation value of index X. It can be calculated as

$$E(X)=(\sum_{i=1}^{n_{st}}\sum_{j=1}^{n_{tf,i}} X(i,j)*D(i,j)/\sum_{j=1}^{n_{tf}} D(i,j))/n_{st} \tag{21}$$

Where $X(i,j)$ and $D(i,j)$ are the index value and duration of time fraction j in simulation i. $n_{tf,i}$ and n_{st} are the number of time fraction in simulation i and total simulation times, respectively. Following are the indices proposed to quantify the performance of IEGS.

1) Wind consumption rate

This index measures the portion that wind energy has been consumed.

$$WCR = E((\sum_{i=1}^{i=nb^e}\sum_{j=1}^{j=n_{wt,i}} P^e_{G_{wf},i,j})/P^e_{wc}) \tag{22}$$

Where P^e_{wc} is the total wind turbines capacity.

2) Gas supplied by PTGs rate

This index measures the portion of gas that transferred from PTGs.

$$S^g = E((\sum_{i=1}^{i=nb^e}\sum_{j=1}^{j=n_{PTG,i}} P^g_{PTG,i,j})/P^g_{total}) \tag{23}$$

Where P^g_{total} represents the total gas load in gas system.

3) Energy exchange rate

The purpose of investment on the interactive components of IEGS is to balance the supply and demand over two system, which is realized via the relocation of electricity generation and natural gas. Here we propose an index to quantity it in system point of view

$$S = S^g + S^e \tag{24}$$

Where S^e is similar as in the gas system. It can be calculated by:

$$S^e = E((\sum_{i=1}^{i=nb^e}\sum_{j=1}^{j=n_{GFU,i}} P^e_{GFU,i,j})/P^e_{total}) \tag{25}$$

V. CASE STUDY

The IEGS test case is composed by a modified IEEE 9-bus power system case [23] and a 7-bus gas transmission system, and 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. In gas system, the production of PTGs was injected and sold into gas bus 5 and 7, for 0.085 and 0.062 $\$/m^3$ [20]. The structure of IEGS is presented in Fig. 2, and the solid lines and dash lines represent electricity branches and natural gas pipelines, respectively.

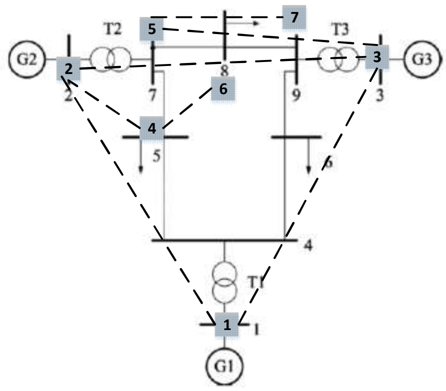

Figure 2. Diagram of IEGS test case

In scenario 1, the capacities of two PTG facilities are 50MW, respectively. The simulation period is 144 hours. The electricity profile of test case is presented in Fig. 3 for illustration.

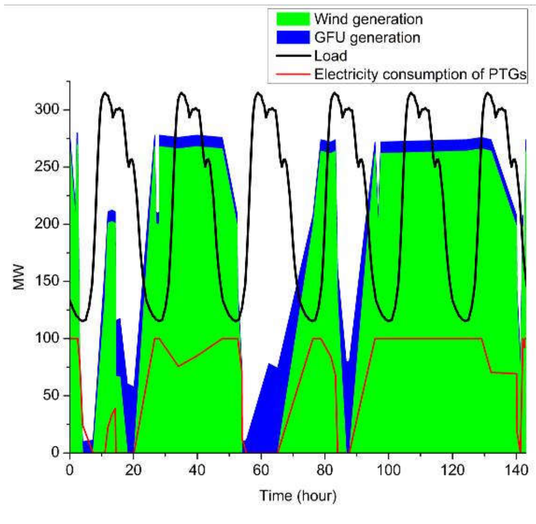

Figure 3. Generation and load profile of test case

As shown in the Fig. 3, the typical load was normalized based on the load curve of non-industrial users in weekdays, collected from EMS (energy management system) in a province of China. As the green area shows, the generation of wind turbines is extremely fluctuated, ranging from its maximum power output to zero. The GFU power output changes accordingly. When wind energy is high, GFU will operating at its minimum output state. Otherwise, it will provide the spinning reserve to balance the difference between energy supply and load. The electricity consumption of PTGs shows strong correlation with wind energy and load level. For instance, from 20 h to 50 h, the electricity consumption of PTGs are all relatively high, as the convert more electricity energy in to natural gas. However, when the load increase in about 33 h, the red line goes down a little.

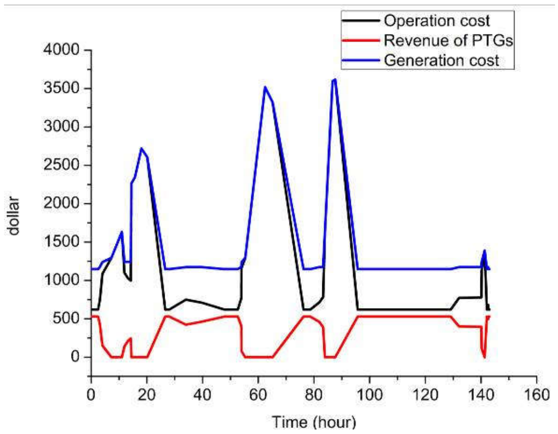

Figure 4. Operating cost composition

Obviously, the operation cost varies over time, as the curves behave in Fig. 4. Generally, in circumstances with high wind penetration, wind shortage comes with an increase of operation cost. However, the revenue of gas selling to the gas system makes certain compensation. Despite such mechanism cutting down the operating cost, worse polarization still occurs over time.

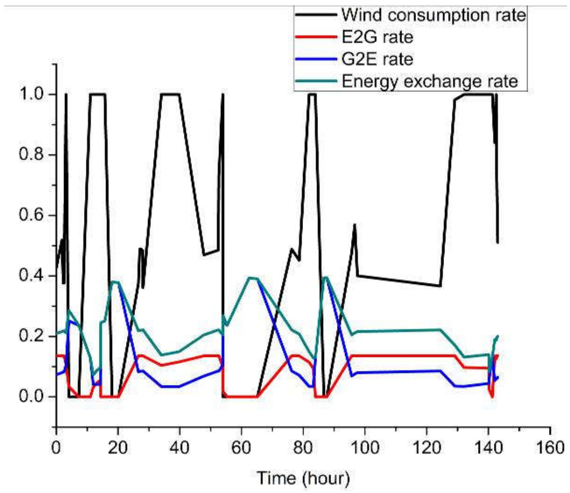

Figure 5. Wind consumption and energy exchange rate

The generalized energy supply and demand will balance in different form all the time, as shown in Fig. 5. In 50 h, the wind energy is abundant. However, the load is at its minimum, therefore, the wind consumption rate was not so ideal. That accounts for the E2G (electricity to gas) rate reaches its maximum value. While in 20 h, the wind energy is barren that G2E rate reached maximum value. The energy exchange rate can be utilized to estimate the activity level of energy exchange devices.

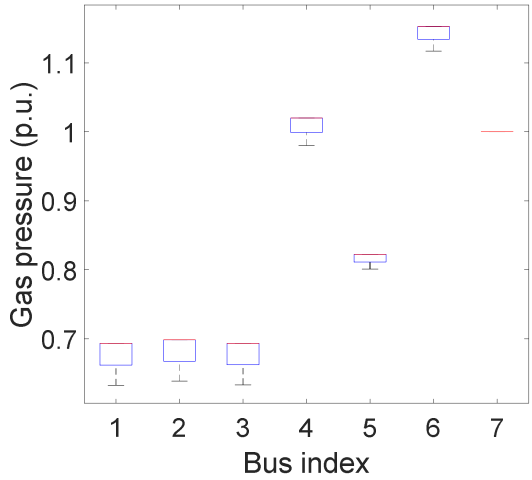

Figure 6. Nodal pressure in natrural gas system

As the optimization proceed as wind fluctuated, the nodal pressures of gas system vary in a certain range as presented in Fig. 6. It has been validated that all the nodal pressures are in the security range with acceptable deviation. Gas bus 7 is set as slack bus that its gas pressure is maintained one p.u. forcibly.

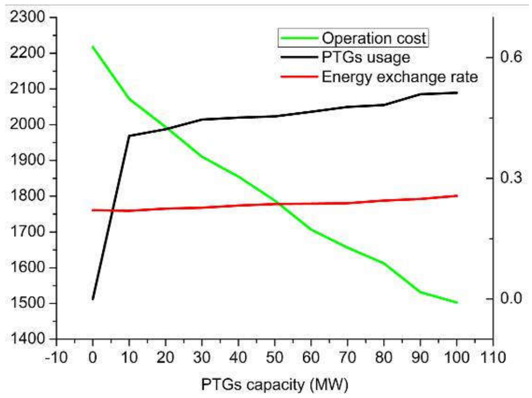

Figure 7. Wind consumption and energy exchange rate

Fig. 7 was drawn based on the simulations with different PTGs capacity, at five MW step size. presented that with the growing capacity of PTGs, the operation cost will decrease along with the growing of energy exchange rate and PTG usage, under the assumption that nor has the investment, operation and maintenance cost been considered.

We use the variance index to estimate the convergence of expectation index. Scenario 2 was set as control group with no PTG facility. After simulation repeated for 2000 times, the indices converge with ideal deviation. For the record, the wind generation cost is set as zero manually, for it will be consumed preferentially.

TABLE I. COMPARISON BETWEEN SCENARIOS

Indices	With two 50MW PTGs	Without PTG
Wind generation (MW)	138.6	138.9
Electricity consumption of PTGs (MW)	51.26	0
GFU generation (MW)	27.38	49.62
Operation cost (\$/h)	1502	2217
Revenue of PTGs (\$/h)	277.3	0
Generation cost (\$/h)	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 ($p.u.^2$)	0.0395	0.0415

As reflected by simulation results, 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. Moreover, the nodal pressures are slightly stabilized, which is beneficial for gas system.

VI. Conclusion

PTGs takes significant position in IEGS for wind consumption. However, the fluctuation and intermittency of wind has not technically been considered in previous researches statistically. In this paper, time sequential Monte Carlo simulation technique was utilized to processing the high wind penetration, for evaluating the impact of large-scale PTG installation on IEGS operation. Comprehensive indices were proposed to evaluate the operation condition of IEGS. With the participation of PTGs, the two system has been bounded intimately, and high energy exchange rate guarantees the energy complementation between two systems. In addition, the operation cost has been reduced on account of the revenue of gas production. To maximize the long-term profit of PTGs, the strategy on economic PTG planning and life-circle assessment are still worth future exploring.

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