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Power-to-gas technology in energy systems: current status and prospects of potential operation strategies

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Abstract Regarded as a long-term, large capacity energy storage solution, commercialized power-to-gas (PtG) technology has attracted much research attention in recent years. PtG plants and natural gas-fired power plants can form a close loop between an electric power system and a natural gas network. An interconnected multi-energy system is believed to be a solution to the future efficient and environmental friendly energy systems. However, some crucial issues require in-depth analysis before PtG plants can be economically implemented. This paper discusses current development status and potential application of PtG plants in the future interconnected multi-energy systems, and further analyzes the costs and benefits of PtG plants in different application scenarios. In general, the PtG plants are not economical efficient based on current technologies and costs. But the situation is likely to change with the development of PtG technologies and interconnected operation of gas-electricity energy system.

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1 Introduction

To cope with the crisis of global climate change, the electric power industries around the world are transiting to sustainable energy systems with increasing capacities of renewable energy sources, such as the wind and solar power plants [1]. Besides, some other energy sources such as the natural gas fired power plants (NGFPs) also show great potentials, as the natural gas (NG) generally enjoys higher efficiency and lower costs over other fossil fuels such as coal and petroleum [2]. Recent development and commercialization of power-to-gas (PtG) plants complete the close loop between electric power systems and the NG networks, making the coordinated operation of multi-energy system become a reality. The combined gas-electricity energy sector demonstrates the trend of the future sustainable multi-energy systems [3, 4].

PtG represents a process that converts water and carbon dioxide into methane, while consuming energy provided by the electricity. This process generally consists of two steps, namely electrolysis and methanation, while the latter one could be optional for electrolyzer-only PtG plants [5, 6]. By March 2013, there are around 30 PtG demonstration plants, most of which are installed in Germany, and the installed capacities of these plants range from several kW to 6 MW [7]. Compared to the capacities of modern power systems and traditional power plants, the capacities of PtG plants are undeniably small at the moment. But the installed PtG capacities are believed to increase rapidly once their cost efficiencies and application prospects can be verified.

The PtG plants act as loads in the electric power systems and as producers in the NG systems. Existing research generally agrees that the PtG plants may benefit the power system in terms of load leveling, wind/solar curtailment [8], ancillary services [9], etc. However, the investment and operation costs of PtG plants should not be neglected, leaving their technical and economic feasibilities in doubt [7]. Especially when the deregulated electricity markets are considered, the implementation of PtG plants becomes more complicated [2].

This paper aims to review the functions of PtG plants, and highlight their possible applications. Although the application and business patterns of PtG plants have been studied in some publications [5–8, 10], in-depth modeling and economic analysis of PtG technologies in electric power and natural gas systems have not yet been systematically addressed. Based on the integration of PtG plants in electric power system and NG network, the potential application scenarios of PtG plants are modeled and the corresponding costs and profits are analyzed in this paper. The reminder of this paper is organized as follows. The capital and operational costs of the PtG plants are discussed in Section 2. The potential applications of PtG plants are analyzed in Section 3, together with their profit assessment. Finally, the conclusions and remarks are given in Section 4.

2 Technical and economic characteristics of PtG technologies

2.1 Technical characteristics

In this paper, the studied PtG plants are assumed to convert electrical energy into methane, which makes them capable of connecting to the NG networks easily.

Although several different methods are available to convert electric power into NG, they share the same reaction principles [10]. The first step is electrolysis, and can be expressed as:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{1}$$

The second step is methanation which normally consumes carbon dioxide as raw materials, shown as:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \tag{2}$$

Combining the reaction equations (1) and (2), the overall process of converting electrical energy into methane can be expressed as:

$$2H_2O + CO_2 \rightarrow CH_4 + 2O_2 \tag{3}$$

1) Electrolysis: the alkaline electrolysis (AE) is the mostly used electrolyzer in commercial PtG plants [11]. Another popular electrolyzer is proton exchange membrane (PEM), which is believed to be more flexible and efficient [12]. However, its capacity is relatively smaller for commercialization at present [7]. Other electrolyzers are still being developed in the laboratory phase, such as solid oxide electrolyzer cell (SOEC) [13].

2) Methanation: the widely adopted methanation method is chemical methanation (CM) [14]. An alternative method, biological methanation (BM) is believed to have higher efficiency [15], while suffering from its limited capacity, similar to the situation of PEM [7].

2.2 Economic characteristics

The economic assessment of PtG plant should be analyzed considering both the capital expenditure (CAPEX) and operational expenditure (OPEX). However, the reported values of CAPEX and OPEX of existing PtG plants and projects vary significantly from one to another in up-to-date literatures [7–10]. In this section, the possible ranges of cost parameters and relatively optimistic values are selected to evaluate the economic characteristics.

1) CAPEX

So far, the demonstrated PtG plants normally employ those mature and commercialized technologies, while the other pilot technologies under research may become available for large-capacity PtG plants in the near future [5]. The investment of PtG plant mainly consists of three components: electrolysis, methanation, hydrogen storage and compression [16, 17]. Among these three parts, the cost of hydrogen storage and compression is the most significant uncertain factor, as its investment is optional and influenced by the operation mode of electrolysis and methanation. In [10], it is reported that the CAPEX of hydrogen storage and compressor may constitute 15%–25% of the total CAPEX of PtG plants. In addition, the costs of real estate and investments of other auxiliary devices such as pipelines and gas conditioners also contribute to the total CAPEX of PtG investment. For simplification, only the CAPEX of electrolysis and methanation will be discussed in this paper as they take up the majority of total CAPEX of PtG plant.

Let P_R, ξ, C_C and C_O denote the install capacity, overall efficiency, CAPEX and annual OPEX of a PtG plant, respectively. The investment costs of current commercial PtG plants with AE & CM are listed in Table 1. Besides, Table 2 demonstrates the forecasted cost coefficients of PEM & BM in 2020, as the PtG technologies are developing rapidly and the costs for PEM and BM may decrease significantly [7]. The capacities of PtG plants are selected as 0.5 MW, 1 MW and 6 MW, respectively. Generally, the

Table 1 Cost coefficients of PtG plants based on AE and CM

P_R (MW)	ξ (%)	Selected ξ (%)	C_C (10^6 \$)	Selected C_C (10^6 \$)	C_O (10^5 \$/year)	Selected C_O (10^5 \$/year)
0.5	50–62	60	2–2.5	2.0	1.8–2.0	1.8
1.0			3.5–4	3.5	2.5–2.8	2.5
6.0			15–17	15	5.5–6.0	5.5

Table 2 Estimated cost coefficients of PtG plants based on PEM & BM in 2020

P_R (MW)	ξ (%)	Selected ξ (%)	C_C (10^6 \$)	Selected C_C (10^6 \$)	C_O (10^5 \$/year)	Selected C_O (10^5 \$/year)
0.5	70–90	80	1.8–2.4	1.8	0.6–0.7	0.6
1.0			3–3.5	3	0.9–1.1	0.9
6.0			10–12	11	3–3.4	3

per-unit capacities of C_C and C_O gradually decrease with the growth of the total installed capacity [7].

The designed lifetime of current AE & CM based PtG plants ranges from 15 to 30 years, while their OPEX include the expenditures on replacements and overhauls. On the other hand, the lifetime of PEM is much shorter, normally 3 to 8 years, while the lifetime of BM is rarely reported in public [10]. As a result, the PEM & BM based PtG plant suffers from a higher annuity fee than that employing AE & CM technologies due to its limited lifespan, even though its CAPEX might be lower based on the cost estimation in Table 2. Thus, the annuity is introduced to further compare the economic characteristics of these two types of PtG plants. The annuity of PtG plants can be calculated as:

$$C_A = C_C \frac{\eta(1+\eta)^{k-1}}{(1+\eta)^k - 1} + C_O \tag{4}$$

where C_A and k are the annuity and designed lifetime of the considered PtG plant, respectively; η denotes the interest rate.

Figure 1 compares the C_A of 6MW AE & CM based and PEM & BM based PtG plants with different lifetimes. In Fig. 1, it is assumed that η is fixed at 5%. It is clearly demonstrated in Fig. 1 that the extension of k will result in significant decreases of C_A for the PEM & BM based PtG plant. The annuity of a 6 MW PEM & BM based PtG plant with the lifetime of 10 years will be lower than that of the AE & CM based PtG plant with the same capacity and lifespan of 20 years. On the other hand, Fig. 1 also illustrates that AE & CM technologies are more cost efficient before considerable breakthroughs of PEM & BM take place.

6 MW AE & CM based and PEM & BM based PtG plants will be analyzed in detail in this paper. Besides Besides CA, the average daily cost, denoted as *Cd*, will be calculated assuming the PtG plants will operate ψ days per year, listed in Table 3. The calculated C_d in Table 3 represents the daily cost of a PtG plant, so that any profitable business model for PtG operations should at least compensate the calculated C_d.

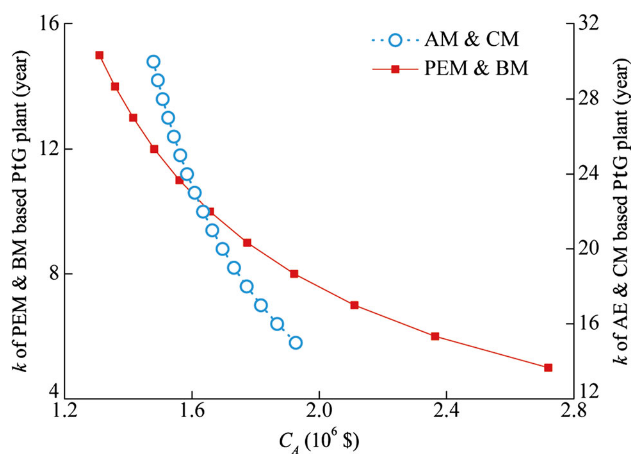

Fig. 1 Comparisons of C_A with different lifetime k

2) OPEX

Similar to the composition of CAPEX discussed in the previous section, the OPEX of a PtG plant is also influenced by multiple factors, including but not limited to:

a. Depreciation and replacement
b. Labor cost
c. Consumption of raw materials (water, carbon dioxide, etc.)
d. Electricity consumption
e. Other OPEX related to storage units and ancillary devices

The first two elements have been taken into account in C_O in the previous section, whereas the others are greatly affected by the operation patterns of PtG plants that special considerations are required.

Table 3 Annuity and daily average costs of different type of PtG plants

Type	P_R (MW)	Selected k (year)	C_A (10^6 \$)	Selected ψ (day)	C_d (10^3 \$)
AE & CM	6.0	20	1.696	330	5.14
				300	5.65
PEM & BM	6.0	6	2.364	330	7.16
				300	7.88

The electricity demand and requirement of raw materials are the most important components, taking up as much as 2/3 of the total OPEX [18]. At the same time, the consumptions of electricity and raw materials will be decided by market prices, operation days per year, and typical daily operation conditions. The cost of raw material consumptions includes the cost of water and carbon dioxide. Although the cost of water can negligible compared with that of electricity, the expenses for carbon dioxide vary a lot depending on its sources. Typically, carbon dioxide can be acquired through carbon capture methodology, biogas and ambient air [17]. Detailed discussions and analysis of these costs will be introduced considering the different application scenarios of PtG plants in Section 3.

It should be noted that C_O in Tables 1 and 2 will also be influenced by the operation patterns of PtG plants, since less frequent operation will lead to lower degeneration costs. Moreover, C_A and C_d in Table 3 will also be affected since they are derived from C_O, but it is somehow very difficult to quantify the exact values of C_A and C_d based on operational strategies of PtG plants. As a result, the influences of operation modes on C_O, C_A and C_d will be neglected in this paper.

3 Operation modeling and profit analysis

A PtG plant consumes much electricity to produce methane for other energy sectors, and is generally considered as a promising means of energy storage for excessive electricity generation from renewable energy sources such as wind farms and photovoltaic parks. On the other hand, a PtG plant also requires reasonable operational modes and business patterns to compensate its expensive costs as discussed in Section 3. Considering the potential functions of PtG plants in the interconnected energy systems, the following application scenarios will be studied in this paper:

1) Independent operation (PtG plant does not participate in any coordinated operation/business associate)
2) Energy storage for renewable energy sources
3) Ancillary service provider for the electric power system
4) Coordinated operation with NGFPs in multi-energy systems

Besides the four aspects mentioned above, the PtG technologies also can be implemented in other energy sectors such as providing renewable fuels in transportation, utilizing waste heat in a heating system and participating in chemical industry [19–22]. However, these extensive applications of PtG technologies will only be briefly introduced, as this paper mainly focused on analyzing the economic potentials of PtG technologies in electric power systems.

3.1 Independent operations

From the perspective of a PtG plant, its income comes from selling NG in the NG markets. At the same time, the PtG plant has to pay for electricity and raw materials that it has consumed. While ignoring the fluctuations of market prices, the daily revenue of a PtG plant operating at its full capacity is calculated as:

$$R_d = \xi P_R(C_{NG} - \alpha C_M) - C_E P_R - C_d \tag{5}$$

where R_d, C_{NG}, C_M, C_E and α are the daily revenue of a PtG plant, the price of NG, the price of raw material, the price of electricity and the coefficient of raw material consumptions per unit NG production, respectively.

Practically, the prices in the electricity market are generally considered to be volatile so that the PtG plant always prefers to purchase electricity when the electricity price is low. In general, the PtG plant will try to maximize R_d through appropriate operational strategies, which does not necessarily mean that the plant will run at its full capacity all the time. Thus, an optimization model can be formulated as follows.

$$\max R_d = \sum_{t=1}^{T_S}((C_{NG}(t) - \alpha C_M)P_{NG}(t) - C_E(t)P_E(t)) - C_d \tag{6}$$

$$\text{s.t.} \quad \tau(t)P_{E,\min}\Delta t \le P_E(t) \le \tau(t)P_R\Delta t \tag{7}$$

$$P_{NG}(t) \ge 0 \tag{8}$$

$$-P_{st,\max} \le P_{st}(t) \le P_{st,\max} \tag{9}$$

$$\xi P_E(t) = P_{st}(t) + P_{NG}(t) \tag{10}$$

$$S_{st,\min} \le \sum_{t=1}^{T_S} P_{st}(t) + S_{init} \le S_{st,\max} \tag{11}$$

$$\tau(t) \in \{0,1\}\ ,\ \forall t \in [1, T_S] \tag{12}$$

where $C_{NG}(t)$, $C_E(t)$, $P_{NG}(t)$, $P_E(t)$, $P_{st}(t)$ and $\tau(t)$ denote the price of NG, the price of electricity, the NG output energy, the electric input energy, stored NG energy and the on-off status of the PtG plant at period t, respectively; T_s and Δt denote the number of daily operating periods and the length of each operation period, respectively; $P_{E,\min}$, $P_{st,\max}$, S_{init}, $S_{st,\max}$ and $S_{st,\min}$ denote the minimal input electric power, maximum stored NG energy per Δt, the initial stored NG energy at the beginning of the operating day, maximum and minimal stored NG energy of the PtG plant, respectively.

The aforementioned model considers the operating constraints of the PtG plant itself, and is suitable to evaluate the profit of PtG plant that does not always operate at its full capacity. For an AE & CM based PtG plant, $P_{E,\min}$ ranges from 5% to 20% of its installed capacity [10]. $P_{E,\min}$ may be as low as 0% for PEM & BM based PtG plants. It should be noted that the operation of PtG plants may also be limited by other factors such as the conditions of electric power and NG networks, and the model should be modified based on real conditions.

As demonstrated in (5), the operation of a PtG plant will possibly be economic when C_{NG} is much higher than C_E. In contrast, the real world C_{NG} is generally lower than C_E. Take the price data in Europe as an example, the average C_E generally ranges from 40 \$ to 70 \$/MWh [23, 24], while the average C_{NG} generally ranges from 30 \$ to 50 \$/MWh [24–26]. Considering the current efficiency of PtG technologies, the PtG plant is not likely to be profitable even though its investment cost is ignored.

Assuming an ideal case where ψ equals to 330 d, C_E and C_{NG} are fixed at 40 \$/MWh and 50 \$/MWh, respectively. For a 6 MW AE & CM or PEM & BM based PtG plant running at full capacity, its daily revenue without considering C_d and C_M will be -1.44×10^3 \$ or 0 \$, respectively. However, the R_d of these two types of PtG plants will drop at -6.58×10^3 \$ and -7.16×10^3 \$ considering C_d, respectively. As a result, it is hardly possible for both types of PtG plants to compensate their CAPEX and OPEX through this operation mode, which is inappropriate for large scale implementation. If the operation of PtG is to be optimized through the model (6)–(12), the plant will stay idle all the time. Moreover, the higher conversion efficiency and shorter lifespan of PEM and BM technologies enable PtG plants to produce a larger capacity of NG, but suffer from higher economic losses at the same time.

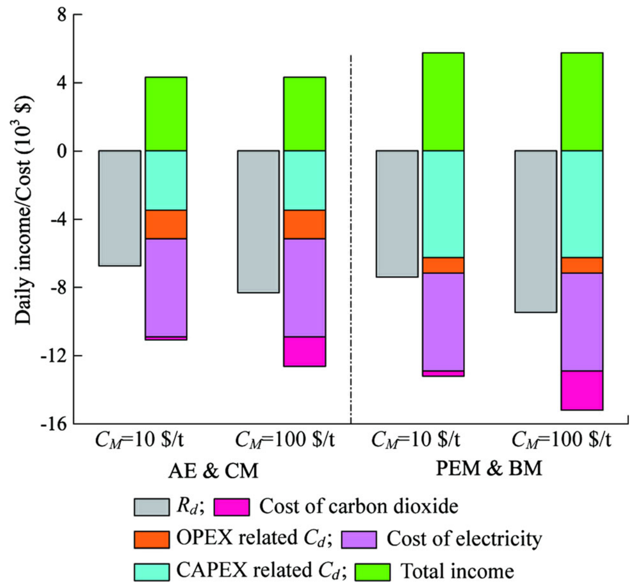

Fig. 2 Composition of daily operating revenue PtG plants

The value of C_M varies depending on the sources of carbon dioxide, and the expenditure for carbon dioxide approximately ranges from 10 \$/t to 1000 \$/t, and the coefficient α is approximately 0.2 t/MWh [8, 18, 27]. Figure 2 compares the income, revenue and cost compositions of PtG plants with C_M price at 10 \$/t (e.g. from fossil sources) and 100 \$/t (e.g. carbon capture from ambient air or industrial emissions), respectively.

As can be clearly observed from Fig. 2, the expenditures for purchasing electricity and C_d make up the greatest part of total cost. The cost of carbon sources also becomes nonnegligible with the increase of C_M. The cost of carbon dioxide is somewhat very complicated to quantify and out of the scope of this paper [27]. Thus, the influences of C_M will be omitted and no further discussions will be included in the rest part of this paper.

Based on the analysis above, the PtG plant is normally very cost inefficient to operate. However, in certain circumstances when the C_E is extremely low (e.g. C_E becomes negative), the PtG plant may become cost efficient eventually. Take the spot market in Denmark as an example, the spot market price in Denmark may become negative due to excessive wind power generation and limited electricity loads after midnight. In such cases, C_E becomes negative, e.g., the lowest C_E could be -60 \$/MWh [26]. Assuming the negative price could last for 24 hours, then R_d becomes 7.82×10^3 \$ and 7.24×10^3 \$ for 6 MW AE & CM and PEM & BM based PtG plants. However, the negative C_E should only be regarded as an uncommon case. The PtG plants must search for other ways to make up for their investment costs.

The NG market prices are generally more moderate than those in the electricity market. If the NG market price is set

Table 4 Maximum economic efficient C_E for different PtG plants

Type	P_R (MW)	Selected ψ (day)	Maximum economic efficient C_E (\$/MWh)
AE & CM	6.0	330	−5.69
		300	−9.24
PEM & BM	6.0	330	−9.72
		300	−14.72

as a fixed value of 50 \$/MWh, the maximum C_E for the economic operation of a PtG plant is listed in Table 4.

3.2 Energy storage for mitigating volatile power outputs from renewable energy sources

With increasing capacities of wind and solar power, the power systems normally require larger energy storages to cope with the volatilities and uncertainties introduced by those intermittent energy sources. Compared with the traditional energy storage methods such as fly-wheels and batteries, the capacities of PtG plants are much larger [5], as the converted NG can be restored in both the NG storage tank and the NG network. On the other hand, a simple PtG plant only converts electrical energy into NG, while other storages could transfer their stored energy back to the power system when needed. A possible solution is the combined operation of PtG plants and NGFPs, which enables the bidirectional energy flows between the power systems and NG networks.

The contribution of a PtG plant to the power systems generally comes from its impact on wind/solar curtailments [1], system reserve cost reduction and operation cost reduction. Typically, the system reserve capacities and operation costs will increase to accommodate the volatile power outputs of renewable energy sources. The consumption of PtG plants will help in leveling the fluctuations of renewable energy outputs, reducing required system reserves, avoiding frequent start-up and shut-down of the conventional power plants, etc. The positive role of PtG plants in power system optimization can be simply demonstrated in Fig. 3.

As illustrated in Fig. 3, the available wind power generation cannot be fully utilized when the system load is low to avoid system imbalance, frequent start-up and shut-down of thermal power plants. By introducing PtG technologies as energy storage solutions, the original curtailed wind power generation will be consumed by PtG plants, thus decreasing or eliminating the wind power curtailments.

The high investment costs and electricity purchasing costs of the PtG plants could possibly be covered through their contributions to the power systems. However, the most important issue becomes their reasonable approach to gain these profits, especially in deregulated electricity markets.

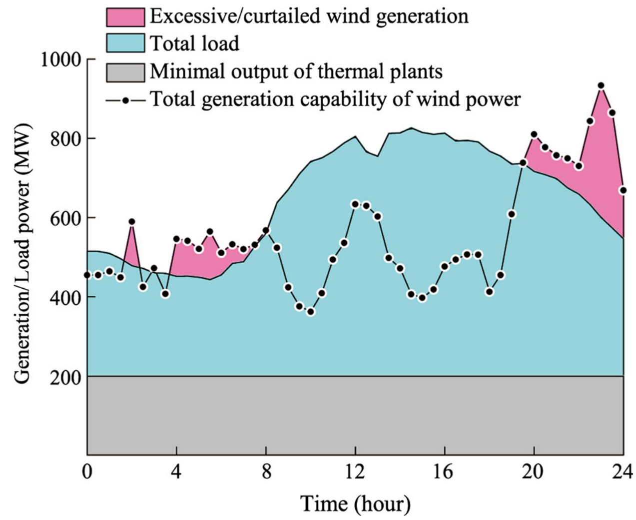

Fig. 3 Demonstration of PtG functions in a power system with wind power curtailment

As demonstrated in the Section 3.1, a PtG plant could possibly make profit by responding to the low C_E caused by volatile renewable energy sources. When operated as energy storage for the intermittent energy sources, the electricity purchasing cost of the PtG plant should be negative as well. Thus, the PtG plant should submit demand bids at negative electricity prices to the system operator for market bidding, which should not be considered as an effective solution.

Several approaches may help with the co-optimization of PtG plants and renewable energy sources:

1) Coordinated operation of PtG plants and renewable energy sources: Through financial methodologies such as long-term contracts, PtG plants could get their needed electricity supplies at relatively lower prices, while providing backup for the renewable energy sources in return. For instance, the renewable generation company is willing to sell its excessive generated power to the PtG plants at half of the market clearing price (MCP). It should be noted that C_E is normally higher than MCP, as it also contains transmission fees and tariffs. As a result, the actual price that the PtG plants pay for the electricity will be reduced by half of the MCP per MWh. In this way, the cost of PtG plants will be compensated. Considering the costs of PtG plants at present and the estimated costs in 2020, this approach will reduce the losses of the PtG plants, but is not likely to change their economic inefficiencies completely.
2) Co-investment of PtG plants: The renewable energy sources could get involved in the investment of PtG plants, which will benefit them from the required storage capacities and other ancillary devices for backup, voltage support, etc. In this way, the capital and operational costs of the PtG plants could be

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significantly reduced. Further analysis is required to evaluate the profit of renewable energy sources in investing the PtG plants, followed by detailed cooperation strategies and revenue splitting schemes.

3.3 Ancillary services

The operations of PtG plants discussed in Sections 3.1 and 3.2 rely on the price signals in the energy market to compensate the high investment costs of PtG plants, while the results are not optimistic due to their high investment costs and high electricity prices in the energy market. In addition to the energy market, ancillary service markets such as regulation and reserve markets could provide additional revenues for PtG plants. Generally, the price for ancillary services, especially the service price for providing regulation service, is comparable to or even higher than the energy market prices. Typically, the PtG plants are capable to participate in regulation market and reserve market, where the prices of these services will provide additional rewards to the PtG plants. Thus, participating in ancillary service provisions provides a feasible alternative for PtG plants to recover their costs.

1) Regulation service: In the regulation market, the PtG plants can provide both regulation up (reducing power demand) or regulation down (increase power demand) services. Based on the characteristics of PtG technologies, regulation down service appears more promising, but the regulation up service normally enjoys higher prices. The daily operation optimization model for a PtG plant in regulation market can be described as:

$$\max R_{all} = R_{d^*} + R_{REG} \tag{13}$$

$$\text{s.t.} \quad R_{REG} = \sum_{t=1}^{T_S} \left(C_{R,up}(t) P_{R,up}(t) + C_{R,dw}(t) P_{R,dw}(t) \right) \tag{14}$$

$$R_{d^*} = \sum_{t=1}^{T_S} \left(\left(C_{NG}(t) - \alpha C_M \right) P_{NG}(t) - C_E(t) P_{E^*}(t) \right) - C_d \tag{15}$$

$$P_E(t) + P_{R,dw}(t)\Delta t \le \tau(t) P_R \Delta t \tag{16}$$

$$P_E(t) - P_{R,up}(t)\Delta t \ge \tau(t) P_{E,\min} \Delta t \tag{17}$$

$$P_{E*}(t) = P_E(t) + P_{RE,dw}(t) - P_{RE,up}(t) \tag{18}$$

$$0 \le P_{RE,up}(t) \le P_{R,up}(t)\Delta t \tag{19}$$

$$0 \le P_{RE,dw}(t) \le P_{R,dw}(t)\Delta t \tag{20}$$

$$P_{RE,up}(t) = \beta_{up}(t) P_{R,up}(t)\Delta t \tag{21}$$

$$P_{RE,dw}(t) = \beta_{dw}(t) P_{R,dw}(t)\Delta t \tag{22}$$

$$\xi P_{E^*}(t) = P_{st}(t) + P_{NG}(t) \tag{23}$$

$$P_E(t)\,,\ P_{E^*}(t) \ge 0 \tag{24}$$

where R_{all}, R_{d*} and R_{REG} denote the total daily revenue, the daily revenue in energy market considering the dispatch of regulation services and the daily revenue for providing regulation services of a PtG plant, respectively. $C_{R,up}(t)$, $C_{R,dw}(t)$, $P_{R,up}(t)$ and $P_{R,dw}(t)$ denote the capacity price for regulation up and down services and the capacity for regulation up and down services provided by the PtG plant at period t, respectively. $P_{E*}(t)$, $P_{RE,up}(t)$, $P_{RE,dw}(t)$, $\beta_{up}(t)$ and $\beta_{dw}(t)$ denote the actual input electric energy considering dispatched regulation energy, the dispatched up and down regulation energy and the probability that regulation up and down capacity will be dispatched at period t, respectively.

The energy price for regulation service, which may exist in some electricity markets, has not been considered in the above model. In this case, the revenue for the regulation energy should be added to the original R_{REG}., which can be calculated as:

$$R_{R,EN} = \sum_{t=1}^{T_S} \left(C_{RE,up}(t) P_{RE,up}(t) - C_{RE,dw}(t) P_{RE,dw}(t) \right) \tag{25}$$

where $R_{R,EN}$, $C_{RE,up}(t)$ and $C_{RE,dw}(t)$ denote the daily revenue of PtG plant for providing regulation energy, the energy price for regulation up and down services at period t, respectively.

The above model is used to calculate the revenue of PtG plants in coordinated energy and ancillary service markets, and the possible dispatched energy for regulation up/down services is considered as well. In general, $P_{RE,up}(t)$ and $P_{RE,dw}(t)$ are very stochastic and hard to predict. $\beta_{dw}(t)$ and $\beta_{up}(t)$ represent the expectation for the dispatch of regulation down and regulation up services based on historical data. Moreover, (8), (9), (11) and (12) should be added to this model to constrain the operation of PtG plants. This model can be adopted in an electricity market where the energy market and ancillary service market are co-optimized, and in an electricity market where the energy market and ancillary service market are cleared separately. For the latter case, the optimized/cleared energy market bids will serve as parameters (e.g. $P_E(t)$) when the bids of PtG plants for ancillary service market are decided.

If the regulation services can be bided separately, a feasible strategy for the PtG plant is to operate at $P_{RE,dw}(t) = P_R$. In this case, the PtG plant successfully reduces its energy purchasing costs and gains revenue for regulation down capacity instead. Furthermore, the net consumed energy during regulation down service can be converted into NG as well. Assuming an ideal case where the regulation down service is always fully dispatched, and the average $C_{NG}(t)$ and $C_{R,dw}(t)$ are 50 \$/MWh and 8 \$/MW, respectively [28]. Based on (13)–(25), the maximum

R_{all} of a 6MW AE & CM based and PEM & BM based PtG plant equals to 332 \$ and -248 \$, respectively.

However, the PtG plants are not always able to bid for the regulation up/down service independently, which is based on different market designs. If the regulation up and down capacity cannot be split, another constraint should be added as:

$$P_{R,up}(t) = P_{R,dw}(t) \tag{26}$$

Let $P_{E,\min}$, the average $C_E(t)$ and $C_{R,up}(t)$ equal to 0, 40 \$/MWh and 25 \$/MW, respectively [28]. The optimal operating strategy when the regulation service cannot be bided independently is $P_E(t) = 3$ MW and $P_{R,up}(t) = P_{R,dw}(t) = 3$ MW, where the ideal R_{all} of the considered AE & CM and PEM & BM based PtG plants are -1.90×10^3 \$ and -2.48×10^3 \$, respectively. Thus, the PtG plants suffer from larger losses for the regulation up service, despite the higher service price. The PtG plants are likely to profit for regulation services on condition that the regulation capacity prices are higher than 51.4 \$/MW and 59.5 \$/MW for the considered two type of PtG plants, respectively. Moreover, the practical regulation capacity price should be higher than the aforementioned ones, as they are calculated based on the ideal case (regulation down service will be fully dispatched, and the regulation up service will not be dispatched at all).

Another important issue concerning the application of PtG plants in an electricity market is their responsive speed. The start-up time of the AE & CM based PtG plants ranges from 30 minutes to several hours, which may become the technical barrier for their participations in the regulation services [10].

2) Reserve market: The reserve market can be analyzed similar to the regulation market, where the PtG plants are not required to be fast responsive to the dispatch signals. However, the PtG plants can only reduce their electricity consumptions for reserve purposes, similar to the regulation up service in the regulation market. Considering the reserve market prices are generally much lower than that of the regulation service market, it is foreseeable that the PtG plants are not likely to benefit considerably from the reserve market. However, the combined participation in regulation and reserve market could be the optimal solution for the PtG plants. For an ideal case where the reserve service will not be dispatched, the PtG plants will gain additional income for the reserve capacity. If the reserve market price is 5 \$/MW [28], the considered PtG plant will get extra 360 \$ each day, based on the model (13)–(26).

3.4 Coordinated operations with NGFPs

Geographically, the PtG plants and the NGFPs are not necessarily correlated. However, they are always able to interact with each other through the NG network. The coordinated operation of PtG plants and NGFPs is believed to be more flexible than their isolated operations.

From the technical perspective, the overall efficiency of the electricity-gas-electricity process is leveled around 30%–40% nowadays [29]. But the introduced gas to electricity process provides an alternative way to utilize the NG converted by the PtG plants. As discussed in the previous sections, the electricity market prices are volatile, especially with increased capacities of intermittent renewable energy sources. The coordinated PtG and NGFP operation will be profitable if the maximum electricity price is at least 2.5 times higher than the minimum price, if the overall efficiency is 40%. Compared with the isolated PtG operation which only becomes cost efficient under negative electricity prices, the coordinated PtG and NGFP operation appears more reliable. Besides, the PtG efficiency could be significantly improved with the development of PEM & BM technologies. The overall electricity-gas-electricity efficiency will be as high as 60% in the future. It is foreseeable that the coordinated PtG and NGFP will become a feasible solution for large-scale integration of PtG plants.

The participation of PtG plants and NGFPs in the coordinated energy and ancillary service markets can be analyzed similar to that in Section 3.3, while their coordination will make them more flexible and competitive. The model described in (13)–(25) can be modified as:

$$\max R_{d^*} + R_{REG^*} + R_{GF} - C_{d,GF} \tag{27}$$

$$\text{s.t.} \quad R_{GF} = \sum_{t=1}^{T_S} \left(C_E(t) - \gamma^{-1} C_{NG}(t)\right) P_{GF^*}(t) \tag{28}$$

$$R_{REG^*} = \sum_{t=1}^{T_S} \left(C_{R,up}(t) P_{R^*,up}(t) + C_{R,dw}(t) P_{R^*,dw}(t)\right) + \sum_{t=1}^{T_S} \left(C_{RE,up}(t) P_{RE^*,up}(t) + C_{RE,dw}(t) P_{RE^*,dw}(t)\right) \tag{29}$$

$$P_{R^*,dw}(t)\Delta t \le \tau(t) P_R \Delta t - P_E(t) + P_{GF}(t) - \sigma(t) P_{GF,\min}\Delta t \tag{30}$$

$$P_{R^*,up}(t)\Delta t \le P_E(t) - \tau(t) P_{E,\min}\Delta t + \sigma(t) P_{R,GF}\Delta t - P_{GF}(t) \tag{31}$$

$$\sigma(t) P_{GF,\min}\Delta t \le P_{GF}(t) \le \sigma(t) P_{R,GF}\Delta t \tag{32}$$

$$0 \le P_{RE^*,up}(t) \le P_{R^*,up}(t)\Delta t \tag{33}$$

$$0 \le P_{RE^*,dw}(t) \le P_{R^*,dw}(t)\Delta t \tag{34}$$

$$P_{RE^*,up}(t) = \beta_{up}(t) P_{R^*,up}(t)\Delta t \tag{35}$$

$$P_{RE^*,dw}(t) = \beta_{dw}(t) P_{R^*,dw}(t)\Delta t \tag{36}$$

$$P_{GF^*}(t) - P_{E^*}(t) = P_{GF}(t) - P_E(t) + P_{RE^*,up}(t) - P_{RE^*,dw}(t) \quad (37)$$

$$P_E(t)\,,\, P_{GF}(t)\,,\, P_{E^*}(t)\,,\, P_{GF^*}(t) \geq 0 \quad (38)$$

$$P_{R^*,up}(t) = P_{R^*,dw}(t) \quad (39)$$

where R_{REG^*}, R_{GF} and $C_{d,GF}$ denote the daily revenue of combined PtG and NGFP coalition for regulation services, daily revenue of NGFP in energy market and the average daily cost of NGFP, respectively. $P_{R,GF}$, $P_{GF,\min}$ and γ denote the installed capacity, minimal output electric power and the efficiency of the NGFP, respectively. $P_{GF}(t)$, $P_{GF^*}(t)$, $P_{R^*,up}(t)$, $P_{R^*,dw}(t)$, $P_{RE^*,up}(t)$, $P_{RE^*,dw}(t)$ and $\sigma(t)$ denote the scheduled output electric energy, actual output electric energy considering regulation services, the regulation up and down capacity of the combined PtG and NGFP coalition, the actual dispatched regulation up and down energy of the combined PtG and NGFP coalition and the on-off status of NGFP at period t, respectively.

Similar to the model in Section 3.3, the constraint in (39) is optional and can be used in the cases where the regulation up and down capacities should be identical. Also, Eqns. (8), (9), (11), (12), (15) and (23) should be added to this model.

However, the coordination of PtG and NGFP will be limited to the conditions of electric power and NG networks. If the PtG plant and NGFP are connected through the energy networks, the constraints of energy networks shall be introduced [30–32], which will not be further discussed in this paper.

Based on the same parameters and assumptions in Section 3.3, and assuming the $C_{d,GF}$, γ and $P_{R,GF}$ are 3.6×10^3 \$, 70% and 10 MW, respectively [33], a comparison between the isolated PtG plant operation and coordinated operation can be made. The possible daily maximum profits considering constraint (39) will be 2.30×10^3 \$ and 1.72×10^3 \$ for the NGFP and the 6 MW AE & CM/PEM & BM based PtG plant. It should be noted that these profits are calculated based on the ideal assumptions, similar to that in Section 3.3.

On the other hand, the coalition of PtG plants and NGFPs is feasible when the total profit of coordination is higher than the revenue sum of each individual entity. While taking the regulation energy profit into consideration and assuming $C_{RE,dw}(t)$ equals to 10 \$/MWh throughout the operating day, Fig. 4 demonstrates the ideal revenue profiles of individual operation and coalition with different values of $C_{RE,up}(t)$.

As can be observed from Fig. 4, the coordination between NGFP and PtG plant will bring extra profit than their individual operation. Since the NGFP benefits more from the regulation down services and the PtG plants are in favor of higher regulation up energy prices, their coordination will be able to utilize their preferences and increase the overall income for regulation services.

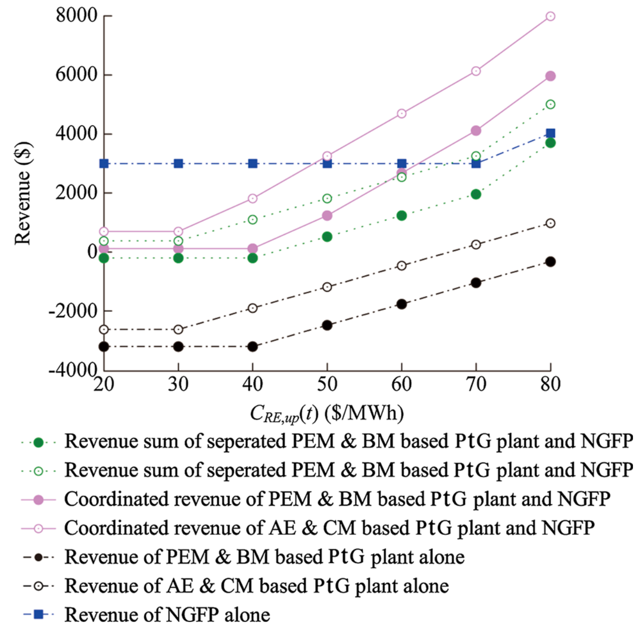

Fig. 4 Revenue comparison of PtG plant, NGFP and their coalition with different regulation up energy prices

However, the coalition may still be impractical to compensate the costs of PtG plants. For 6 MW AE & CM and PEM & BM based PtG plants, the revenue of a PtG and NGFP coalition is higher than the individual profit of NGFP when $C_{RE,up}(t)$ is approximately 48 \$/MWh and 63 \$/MWh, respectively. Thus, the PtG plants may eventually make profit by splitting the extra profit of the coalition based on certain principles.

The above analysis overlooks the physical constraints of the NG network. Typically, the NG transmission can only be unidirectional, and this limits the topology structure selection between collaboratively operated PtG plants and NGFPs. Besides, the pipeline capacity, nodal NG pressure, and NG market rules also have impacts on the coordination of PtG plants and NGFPs [2]. Detailed modeling of the combined gas-electricity energy systems and in-depth study on the optimal operating strategy of PtG plants and NGFPs in both the electricity and NG markets are demanded to clarify the benefits and responsibilities of the coordinated PtG plants and NGFPs.

3.5 Remarks on other applications

As stated at the beginning of this section, the four application scenarios discussed above mainly focus on analyzing the influences of PtG plants on the electric power system and the feasibility of their corresponding business models. Considering the cross-sector characteristics of PtG technologies, PtG plants may be profitable in these following areas:

1) Waste heat utilization and energy hubs

The methanation reaction is exothermic, and the waste heat during this process is one of the major contributors to the limited efficiencies of PtG plants [21]. The released heat may be utilized in residential heating systems, steam power cycles, carbon sources etc. [10, 34]. Based on the energy hub concept [35], the utilization of the heat produced during PtG process for domestic and industrial heating will improve the overall energy utilization efficiency, and bring extra financial rewards for the PtG plants.

2) Transport sector with fuel cell, compressed natural gas (CNG) and electric vehicles

Either the hydrogen produced through electrolysis or the methane produced through the entire PtG process can be used/sold as transport fuel for fuel cell based or CNG based vehicles [21, 36]. Furthermore, the electric vehicles can be charged considering the participation of NGFPs. For individual vehicle owners, they are motivated to interact with the PtG plants and NGFPs if they can provide cheaper charging prices. For PtG plants, this business mode may indicate higher conversion efficiency and lower cost for carbon sources (i.e. providing hydrogen for fuel cell vehicles). Also, the PtG plants may receive additional rewards for the biofuel they produced based on energy policies and regulations [8].

In addition, the PtG technologies should extend their business opportunities to become financially viable investment choices [18]. All types of incomes should be evaluated and made use of, e.g. selling intermediate products such as oxygen and participating in markets and frameworks for carbon emission.

4 Conclusion

Based on the investigations, it is clear that PtG plants are not economic efficient based on either the current AE & CM technologies, or the PEM & BM in the near future. On the other hand, the CAPEX and OPEX of PtG plants are believed to decrease considerably in the following years, which might make a great difference.

The participation in electricity ancillary service markets and the coordinated operation with NGFPs are the two promising applications for PtG plants. The calculated costs and incomes in this paper are based on ideal assumptions, where the situations will be worse in the real world. It can be concluded that the operation of PtG plants are financially feasible in certain circumstances.

However, the commercialization of PtG plants is still promising, since the price of NG is constantly rising in recent years. The flexibility of PtG plant makes it profitable through reasonable operation among multiple energy sectors. Also, this paper focuses on the gas-electricity combined energy system, while other energy systems such as heating, cooling and transport can be integrated according to real world conditions. With the increasing awareness and emphases on the global sustainable energy transformation, energy storage solutions such as PtG technologies will benefit more from energy policies. Moreover, the coordinated multiple energy systems with reasonable PtG implementations are more likely to provide alternative solutions for future decarbonized energy prospective.

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