Stochastic Optimal Operation of Coordinated Natural Gas and Electricity Network with a focus on power-to-gas technologies and wind power curtailment

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Abstract. As the need for renewable energy sources like wind energy grows to support worldwide efforts to reduce carbon footprints. There is an urgent need to find a solution to the challenges of its intermittent nature and the issue of curtailment. To balance the current erratic supply and demand, creative energy solutions are needed. Power-to-gas (P2G) technology uses water electrolysis to convert excess renewable energy into hydrogen gas, offering a workable alternative for the use of excess wind energy to address the issues of erratic supply and demand. This paper presents a stochastic optimal operation of coordinated natural gas and electricity network model which balances the electricity and gas demand considering power-to-gas technologies and wind power curtailment. To show that the suggested model is effective, case studies with/without P2G are carried out on a coordinated UK 16-bus network and a Belgian 20-node gas network. Simulation results illustrate that P2G was beneficial in the operation of the proposed model in terms of total operational cost reduced from 542971.9 M/$ to 538538.5 M/$ and wind curtailment reduced from 79.0% to 71.5%.

Keywords: Electricity network, Natural gas network, Power-to-gas, wind power curtailment.

1 Introduction

1.1 Background and motivation

The global climate change and worldwide energy crisis are two key issues for achieving sustainable development, and rising energy needs are creating additional environmental problems. [1]. It is believed that it is possible to overcome these issues by incorporating renewable energy resources (RES), increasing energy utilisation efficiency, and reducing CO2 emissions. The Paris Agreement states that the energy sector is crucial for limiting climate change. [2]. 80%-95% of greenhouse gas emissions are anticipated to be decreased by speeding the decarbonization of energy systems and boosting the penetration of renewable energy sources [3]. The global energy structure must be changed to one based on renewable energy sources (RES) to achieve these lofty targets. The share of RES in the electricity system is anticipated to reach 85% by 2050, with solar and wind power generation accounting for most of this share. According to an estimate by the International Energy Agency, wind generation in European nations is anticipated to surpass 2000 TWh by 2030. In 2019, 4.18 trillion kWh of electricity was produced in the United States, with RES generation accounting for 19% of the total energy [1].

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The increasing utilisation of wind energy to generate electricity have achieved greater development globally in recent years. As the usage of renewable wind technology expands globally, the power systems' reliance on intermittent renewable energy sources is challenged on both an economic and a reliable basis. The fact that a large percentage of wind energy is restricted due to the temporal and spatial mismatch of supply and demand is one of the major obstacles to the production of wind power. To address the problems caused by the reduction of wind power. Based on their coupling technique, research on combined electric power and natural gas systems is extensive [4]. Electricity and gas networks are connected using power-to-gas (P2G) facilities and gas-fired generators. The P2G process is designed to transform excess wind energy into synthetic natural gas or hydrogen, which will then be supplied to the gas network or sent to gas-fired generators to produce electricity. As a result, the P2G process limits the natural gas supply from natural gas wells, which has an impact on the gas system's cost structure. However, the use of GFGs will limit the power production of coal-fired generating units, which will have an impact on the electricity system's cost structure. Therefore, a key factor in reducing wind power is the functioning of coordinated electricity and gas systems with P2G plants.

1.2 Literature review

In recent years, practical coordinating techniques for the Systems that combine gas and electricity have been discussed. The coordinated gas and electricity network's effects of electrical demand response are examined by the authors in [5]. [6] created a mixed integer linear programming security constraint for the best possible flow of gas and electricity. A coordinated stochastic model is presented in [1] to analyse the integration of the transmission networks for natural gas and electricity. The authors in [7] studied the steady state analysis of a network that integrates natural gas and power while considering P2G plants. Regarding natural gas prices and gas output from renewable sources, [8] evaluates the possibility of the P2G with the incorporation of seasonal storage. However, the reviewed works were considered at the transmission level.

In contrast to previous work, the proposed gas network and electricity network are coupled by considering the energy conversion of GFGs and P2G plant at the distribution level, and the goal of this paper is to minimise the total operation cost (TOC) of the coordinated gas and electricity network, which is the sum of the price of producing natural gas and the cost of producing electricity. The nonlinear optimization model of the natural gas network is linearized to improve the computation efficiency and have a global optimum solution.

The following is a summary of the paper's main contributions:

1) The gas and electricity networks are considered simultaneously to build an ideal operation model. The model of the gas network is linearized to increase computation efficiency, and the operating model is built as an easily solvable MILP problem.
2) The proposed model includes the Power-to-Gas (P2G) technology paradigm, which transforms surplus wind energy into gas and establishes a two-way connection between the networks for both gas and electricity.
3) The outcomes demonstrate that the P2G procedure is successful in raising the rate of wind energy utilisation. It has also been demonstrated that the P2G process can help lower natural gas use and emissions.

The remaining section of the paper is structured as follows: Section 2 introduces the suggested mode's system description. Section 3 outline the problem formulation of the proposed model. Section 4 demonstrates the simulation result are drawn in section. Section 5 discussed the conclusion and future research direction.

2 System description

Figure 1 shows how the coordinated natural gas and electricity networks are connected through power-to-gas (P2G) plants and gas-fired generators (GFGs). The gas-fired generator serves as both a load and a generator in the natural gas and electrical networks. The power load is satisfied by the gas-fired generators (GFGs) and wind power. Residential gas loads and GFGs are supplied with natural gas from the gas well. Wind energy surplus can be used by the power-to-gas plant to create synthetic natural gas (SNG), which is then fed into the natural gas network or the GFGs during periods of high peak demand.

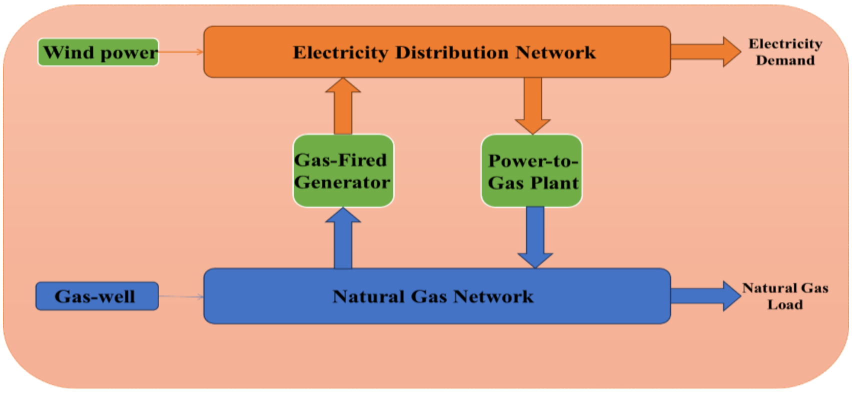

Fig. 1. Proposed structure of coordinated Natural gas and electricity networks.

3 Problem Formulation of the Proposed Model

This section develops the suggested model while considering wind energy and P2G, which aims to dispatch power and gas sources as efficiently as possible while meeting the physical and security requirements of the electricity and gas networks.

3.1 Objective Function

The coordinated electric power and gas network concept is a tool for improving the infrastructure for gas and electricity. The goal of the suggested model is to reduce total operating costs (TOC), which are calculated as the product of the cost of gas supply from the gas well and the cost of power generation by gas-fired generators while satisfying gas and electricity demand. The model includes a thorough representation of the gas network, including assets like gas pipelines and gas wells, as well as an AC load flow of the electricity network. For simplicity of the model, the gas storage and compressors are not considered in this paper. The interaction between the two networks is through gas turbine generators and a P2G unit connected to both networks.

$$Min = \ Cost_{Gen}^{power} + \ Cost_{Prod}^{gas} \quad (1)$$

Where

$$Cost_{Gen}^{power} = \sum_{t=1} \sum_{i\Omega_{GFG}} \rho_i^{Gas_{GFG}^{price}} \ P_{i,t}^{GFG_{power}} \quad (2)$$

$$Cost_{Prod}^{gas} = \sum_{t=1} \sum_{nm\Omega_{GW}} \rho_{nm}^{Gas_{GW}^{price}} \ P_{nm,t}^{GW_{Gas}} \quad (3)$$

Equation (2) is the Cost of generating electricity which consists of the cost coefficients of GFGs and the real power outputs of the GFGs. Equation (3) is the cost of gas production which consists of the cost of producing natural gas for gas wells per kcf and the nodal gas production at the gas well.

3.2 Constraints

3.2.1 Electricity network model

The electricity network is illustrated in this paper by the AC power flow [9] Equations (5) and (6), respectively, depict the real and reactive power flow on a branch and nodal power flow balancing equation. where the active and reactive power on branch linking buses i and j, respectively, are denoted by $P_{i,j,t}$ and $Q_{i,j,t}$. The voltage magnitudes at buses i and j are $V_{i,t}$ and $V_{j,t}$, respectively. The voltage angles at buses i and j are $\theta_{i,t}$ and $\theta_{j,t}$, respectively. The voltage angles $\theta_{i,t}$ and $\theta_{j,t}$ differ by an angle called θ_{ij} . The conductance and admittance of the branch joining buses i and j are denoted as $G_{i,j}$ and $B_{i,j}$, respectively.

3.2.2 Nodal Power flow constraint:

The power balance is satisfied by the power generated from GFGs, wind power, power consumed by P2G units and the electric load demand as represented in equation (4).

$$\sum_{i\in\Omega_{GFG}} P_{i,t}^{GFG_{power}} + \sum_{i\in\Omega_{WT}} P_{i,t}^{WT} - \sum_{i\in\Omega_{P2G}} P_{i,t}^{P2G^{power}} - \sum_{i\in\Omega_{P2G}} P_{i,t}^{load^{power}} = \sum_{\mathrm{i,j,t}} \mathrm{P_{i,j,t}} \quad (4)$$

Where

$$P_{i,j,t} = V_{i,t}V_{j,t}\left[G_{i,j}Cos\left(\theta_{i,t} - \theta_{j,t}\right) + B_{i,j}Sin\left(\theta_{i,t} - \theta_{j,t}\right)\right] \quad (5)$$

$$Q_{i,j,t} = V_{i,t}V_{j,t}\left[G_{i,j}Sin\left(\theta_{i,t} - \theta_{j,t}\right) - B_{i,j}Cos(\theta_{i,t} - \theta_{j,t}\right] \quad (6)$$

$$V_i^{Min} \leq V_i \leq V_i^{Max} \quad (7)$$

$$P_{i,t}^{WT,Min} \leq P_{i,t}^{WT} \leq P_{i,t}^{WT,Max} \quad i \in \Omega_{WT}, \forall t \quad (8)$$

3.2.3 Gas-Fired Generators

The gas-fired generators (GFGs) are natural gas loads in the natural gas network since they use natural gas to produce electricity. Equation (9), which depicts the energy conversion, shows how electricity is produced from natural gas use. Then, equation (10), illustrates the gas-fired generator's security restrictions. The GFGs ramping rate is represented in equation (11).

$$P_i^{GFG_{Min}} \leq P_{i,t}^{GFG} \leq P_i^{GFG_{Max}} \quad i \in \Omega_{GFG}, \forall t \quad (10)$$

$$-P_i^{GFG_{down}^{RAMP}} \leq P_{i,t}^{GFG} - P_{i,t-}^{GFG} \leq P_i^{GFG_{up}^{RAMP}} \quad i \in \Omega_{GFG}, \forall t \quad (11)$$

3.2.4 Constraints on Power to gas technology.

The inclusion of P2G facilities enables the gas network to use excess electricity from the power system, particularly for wind energy that is oversupplied. The chemical reaction is represented in two stages as follow: $2H_2O \rightarrow 2H_2 + O_2$ and $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O.$ With some efficiency, electrolysis is used in the first phase to create gaseous hydrogen. Proton exchange membrane (PEM) technology is advantageous for the P2G process because of its faster ramping rates, which can better tolerate variations in wind power [10]. H2 produced in the first phase can be saved for later use or added to natural gas and pumped into the gas network. SNG is produced in the second stage. Its efficiency as a secondary method of utilising H2 will unavoidably be lower than that of the primary method. However, the SNG process utilises atmospheric CO2, resulting in a reduction in CO2 emissions and further environmental advantages. Consuming electricity from the grid (ideally redundant wind energy) can be used to power both activities. According to (13), P2G facilities can be thought of as gas suppliers that use wind energy that has been restricted with a particular level of efficiency. P2G facilities are required to store and inject natural gas into the gas system in preparation for the subsequent dispatch period [11].

The following coupling restrictions must be satisfied while the coupled gas-electric networks are in use:

3.2.5 Constraints on the P2G power

$$P_{i,t}^{P2G^{Power_{Min}}} \leq P_{i,t}^{P2G^{power}} \leq P_{i,t}^{P2G^{Power_{Max}}} \quad i \in \Omega_{P2G}, \forall t \quad (12)$$

Equation (13) limits the energy conversion's efficiency during P2G conversion, whereas equation (14) limits the ramping rate.

$$P_{i,t}^{P2G^{power}} = \left(\frac{\eta_i^{P2G} P_{i,t}^{P2G^{Gas}}}{HHV^{Gas}}\right) \quad i \in \Omega_{P2G}, \forall t \qquad (13)$$

$$-P_i^{P2G_{down}^{RAMP}} \leq P_{i,t}^{P2G^{power}} - P_{i,t}^{P2G^{power}} \leq P_i^{P2G_{up}^{RAMP}} \quad i \in \Omega_{P2G}, \forall t \qquad (14)$$

The P2G units active power consumption is denoted by $P_{i,t}^{P2G^{power}}$. The natural gas flow produced by the P2G unit is $P_{i,t}^{P2G^{Gas}}$, and P2G stands for the P2G unit's conversion efficiency, and HHV^{Gas} is SNG's high heat value (39.5MJ/m^3).

3.3 Network Steady State Model for Natural Gas

The essential elements of the gas network used in this paper include gas pipelines, gas-well (Gas supply) and gas loads [12]. The steady state mathematical model is used in this study to model the natural gas network. The gas network operates under similar equity and inequality restrictions to the electricity network.

3.3.1 Nodal natural gas flow equation:

Equation (15) depicts the gas network nodal balance, when the total injection and outflow on gas node n are equal.

$$\sum_{nm\Omega_{f_p}} \left(f_{p,nm,t}^{out} - f_{p,nm,t}^{in}\right) + \sum_{nm\Omega_{GW}} P_{nm,t}^{GW} + \sum_{i\Omega_{P2G}} P_{i,t}^{P2G^{Gas}} - \sum_{i\Omega_{GFG_{load}^{Gas}}} P_{i,t}^{GFG_{load}^{Gas}} = Gl_{nm,t} \qquad (15)$$

3.3.2 Gas supply and load:

Like how electricity generation and demand are in the electrical system, the supply and demand for gas are balanced and limited within reasonable ranges [13]. The majority of the gas is supplied through gas wells, which include constrained by the gas flow's upper and lower bounds as shown in Equation (16):

$$S_n^{Min} \leq S_{n,t} \leq S_n^{Max} \quad n \in \Omega_{GW} \qquad (16)$$

Residential, commercial, or industrial buildings may be the source of the gas load, which is crucial to the connectivity of the integrated systems for gas-fired generating units. The upper and lower generation limits of GFGs, as shown in equation (17), also place restrictions on the gas load.

$$Gl_n^{Min} \leq Gl_{n,t} \leq Gl_n^{Max} \quad (17)$$

3.3.3 Gas Pipelines:

Gas pipelines carry natural gas from gas wells to gas consumers. Two different types of pipelines exist: active pipelines and passive pipelines. The active pipes have compressors that may raise the gas pressure in the pipelines, which increases the gearbox capacity. Even though gas pipelines can be either active or passive, only the passive pipelines are taken into consideration in this paper. To model the flow of natural gas through gas pipelines, the Weymouth equation is applied [14].

$$f_{p,nm,t} = sgn(Pr_{n,t}, Pr_{m,t}). C_{nm}\sqrt{\left|Pr_{n,t}^2 - Pr_{m,t}^2\right|} \quad (18)$$

$$sgn(Pr_{n,t}, Pr_{m,t}) = \begin{cases} 1 & Pr_{n,t} \geq Pr_{m,t} \\ -1 & Pr_{n,t} < Pr_{m,t} \end{cases} \quad (19)$$

$$Pr_{n,t}^{Min} \leq Pr_{n,t} \leq Pr_{n,t}^{Max} \quad (20)$$

Where C_{nm} is the gas pipeline constant, which varies with respect to temperature, length, friction, diameter, and the compositions of natural gas. Gas flow through the gas pipeline's direction is represented by the function sgn$(Pr_{n,t}, Pr_{m,t})$. When node n pressure exceeds node m, it is equal to one; otherwise, it is -1. According to equation (19), each node's pressure must be maintained within a specific range. To increase the effectiveness of computing, The Taylor-series expansion linear function can be used to solve the Weymouth gas flow function in equation (18), which several common optimisation approaches cannot directly solve since it is nonlinear and nonconvex [15].

3.3.4 Model of the Gas Network Linearization

In this paper, the Taylor's-series linear function is used to linearize equation (18) non-convex part. Equation (21), with the given pressure values of Pr_n and Pr_m , yield the first-order Taylor series equation (18).

$$f_p(Pr_n, Pr_m) \leq f_p(Pr_N, Pr_M) + \frac{\delta f_p}{\delta Pr_n}(Pr_n - Pr_N) + \frac{\delta f_p}{\delta Pr_M}(Pr_m - Pr_M) \quad (21)$$

To divide the range of node pressures for the inlet and outlet nodes, introduce a set of Z evenly distributed points. This produces Z tuples, designated as $(Pr_{N,Z}, Pr_{M,Z})$ for pipeline p, where Z=1, 2, ……, Z. Therefore, substitute a set of linearized inequality constraints for the nonlinear Weymouth equation (18) as:

$$f_{p,t} \leq C_{nm} \frac{Pr_{N,Z}}{\sqrt{Pr_{N,Z}^2 - Pr_{M,z}^2}} Pr_{n,t} - C_{nm} \frac{Pr_{M,z}}{\sqrt{Pr_{N,Z}^2 - Pr_{M,z}^2}} Pr_{m,t} \quad (22)$$

For each pipeline p (from node n to node m), only the Z inequality constraint that most closely approaches the original constraints (18) will be binding [16].

4 Case Study

4.1 System Description

A coordinated natural gas and electricity network used in the proposed model is represented in Figure (2), which is composed of the UK 16-bus electricity distribution network and a Belgian 20-node natural gas network [12]. All five of the candidate GFGs in the electricity network used in this model are located on bus numbers #1, #3, #5, #15, and #16. Two candidate wind farms and one P2G plant are located at bus #6, #13, and #7, respectively. The Belgian 20-node natural gas network consists of Three gas wells, 24 pipelines and gas load at most of the gas node. Both networks are coupled at node J1 (Zeebrugge), J7 (Gent), J9 (Berneau), J10 (Liege), J14 (Peronnes) and J17 (Wanze). The parameters of Belgian-node Natural Gas Network are shown in Table 1, while the main parameters of the GFGs are shown in table 2. [17] contains a list of the precise specifications for the electricity and natural gas networks. The forecasted hourly electricity load, Natural gas load, and wind power output curves are shown in Figure (3) The P2G plant has a maximum capacity of 40MW and the efficiency of the P2G plant is set at 68% for gas production for the hourly generation dispatch across a 24-hour period, simulations are considered. All simulations were implemented using generalised algebraic modelling systems (GAMS) soft on an 8GB-1.4GHz RAM, Core i7 intel PC.

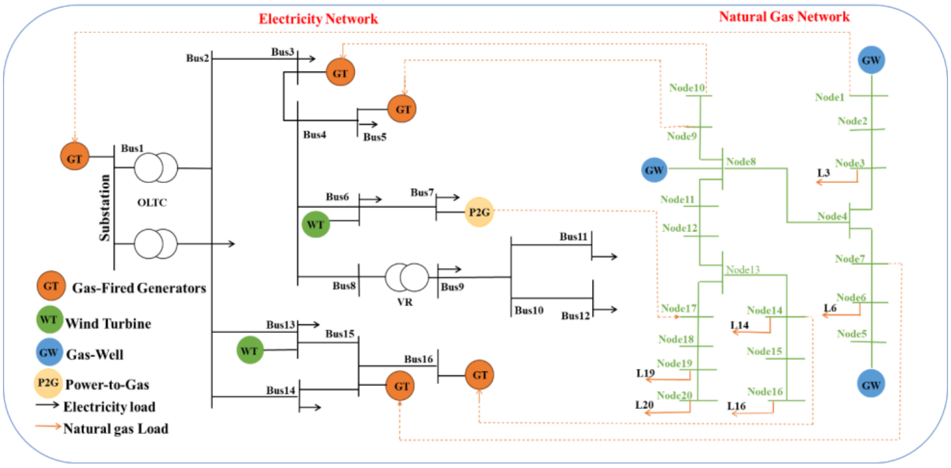

Fig. 2. Coordinated 16-bus UK Distribution Electricity Network and 20-node Belgian Natural Gas network.

Table. 1. Belgian Natural Gas Network Parameters

Gas Node	Town Name	Pr^{Min}	Pr^{Max}	Supply cost
1	Zeebrugge	0.00	77.00	2.28
2	Dudzele	0.00	77.00	2.28
3	Brugge	30.00	80.00	0.00
4	Zomergem	0.00	80.00	0.00
5	Loenhout	0.00	77.00	2.28
6	Antwerpen	30.00	80.00	0.00
7	Gent	30.00	80.00	0.00
8	Voeren	50.00	66.20	1.62
9	Berneau	0.00	66.20	0.00
10	Liege	30.00	66.20	0.00
11	Warnand	0.00	66.20	0.00
12	Namur	0.00	66.20	0.00
13	Anderlues	0.00	66.20	1.68
14	Peronnes	0.00	66.20	1.68
15	Mons	0.00	66.20	0.00
16	Blaregnies	50.00	66.20	0.00
17	Wanze	0.00	66.20	0.00
18	Sinsin	0.00	63.00	0.00
19	Arlon	0.00	66.2	0.00
20	Petenge	25.0	66.20	0.00

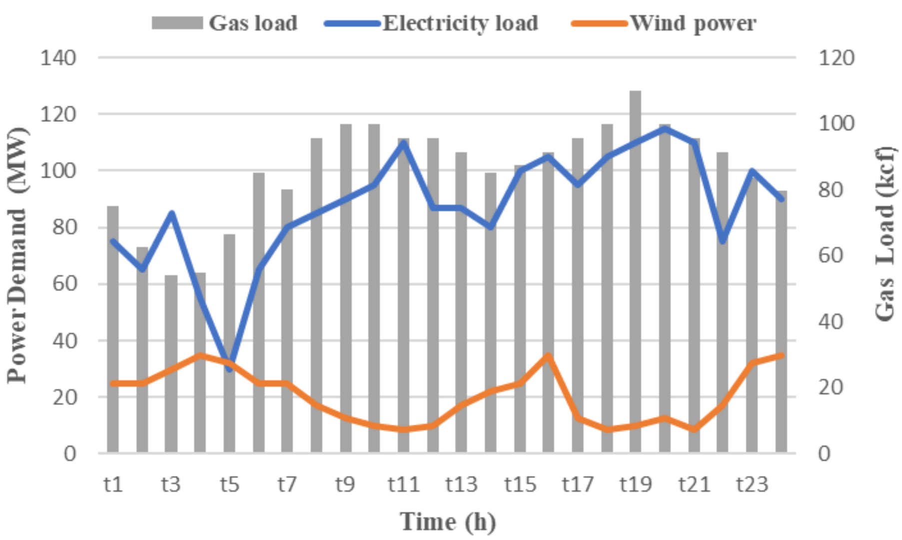

Fig 3. Energy forecasting for wind, electricity, and gas

Table 2. Main Parameters of the Gas-fired generator units

S/No	Gas-fired Generators	Maximum power capacity (MW)	Minimum power output (MW)	Maximum Ramping rate (MW/h)

1	GFG1	250	120	50
2	GFG2	220	100	50
3	GFG3	250	80	50
4	GFG4	200	100	50
5	GFG5	200	120	50

4.2 Simulation Result and Analysis

To verify the effectiveness of the proposed model and analysed the economy of the P2G plant in terms of operation. The proposed model is examined using two case studies.

Case 1: coordinated gas and electricity network optimization scheduling without considering P2G.

Case 2: Coordinated gas and electricity network optimization scheduling considering the P2G.

The P2G technology taken into consideration in this paper allows for extra wind power to be dispatched to produce natural gas. It is an indirect method of using wind energy. Table 3 compares the dispatch results with and without P2G technology. Figures 4 and 5 compare the dispatched wind power in cases 1 and 2, respectively. The entire operating cost for the electricity system is lowered by 4433.4M/$ over the course of a day when P2G was deployed, as shown in Table 3. The total amount of natural gas produced by the P2G process is 3705.5 kcf. Due to the P2G process, the utilization of wind energy increased from 71.5% to 79.0%. The P2G process generates natural gas that partially satisfies gas demand and lessens the influence of gas network restrictions on dispatch results. As part of the natural gas demands are fulfilled by the P2G plant, higher wind power utilization reduces the delivery of gas from the gas well to the GFGs, which results in a reduction on natural gas consumption from the gas well of 13996.4 kcf. Emission reduction is an advantage of P2G plants in addition to increased wind power utilisation and decreased natural gas use. [18] states that the reduction in CO2 emissions from P2G-produced synthetic natural gas is 180 kg/MWh. Therefore, 227,600 kg less CO2 was emitted within a 24-hour period. The integration of P2G plant into integrated gas and electricity networks can improve system operation costs, boost energy utilisation efficiency, and decrease energy consumption and emissions. The results show the benefit of P2G technology and verify the feasibility for the reasonability of optimal operation strategy proposed in this paper.

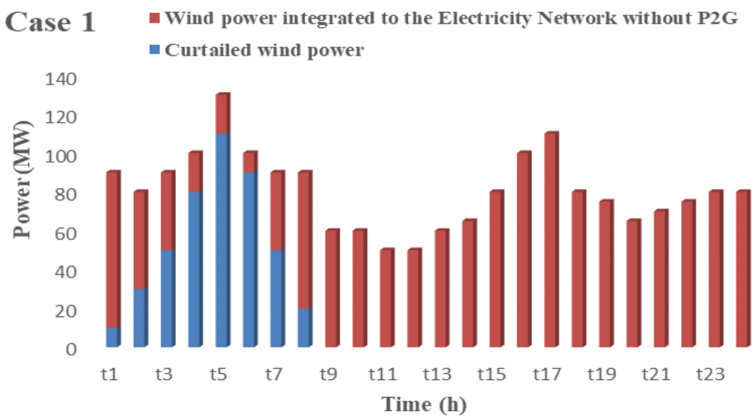

Fig 4. Electricity dispatch results from wind power in the Electricity Network Without P2G (Case 1).

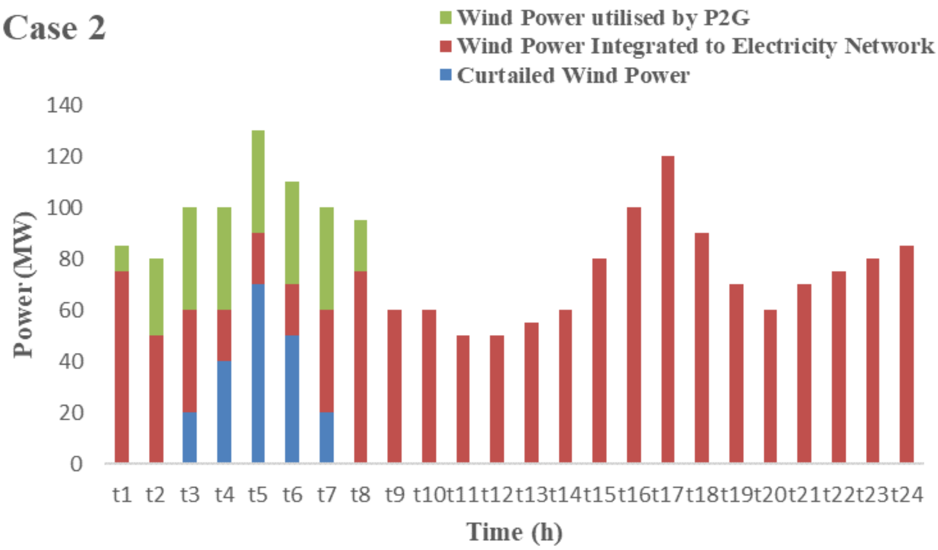

Fig 5. Electricity dispatch results of wind power in the Electricity Network with P2G (Case 2).

Table 3. Results Comparison with and Without P2G Technology

	Electricity Network Cost (M/$)	Amount of Gas consumption (kcf)	Use of Wind power (%)	Amount of Gas produced by P2G (kcf)
Without P2G	542971.9	165296.9	71.5%	0
With P2G	538538.5	151300.5	79.0%	3705.5

4.2.1 Summary of the Impact of P2G Plant

In this paper, P2G plants are viewed as the answer to the problems caused by wind power volatility. Off-peak wind energy surplus is converted to gas, which is used in the gas network. To confirm the relevance of the P2G plant in this paper. A comparison study of two case studies with and without P2G plants was carried out. Table 3 compares computation results with and without P2G plants. According to the results of the model, the rate of wind power curtailment drops from 79% to 71.5% with the addition of 40 MW P2G. Additionally, when the P2G was used to use extra wind power to create synthetic natural gas in case 2, the natural gas consumption from the gas well reduced from 165296.9 kcf to 151300.5 kcf. The operation's cost was ultimately decreased from 542971.9 M/$ to 538538.5 M/$.

5 Conclusion

This paper proposes an economic dispatch model for power-to-gas and wind-powered integrated natural gas and electricity systems. A model for the optimal operation of the electricity and natural gas networks is developed. Here is a summary of the contributions:

(1) The coordinated natural gas and electrical systems mathematical model is presented. The combined system operator distributes supplies simultaneously and economically for both the gas and electrical networks.

(2) To use the redundant wind power, P2G process is linked into the integrated natural gas and electricity networks to ensure optimal performance. The reciprocal exchanges between gas and electricity networks are realised via P2G and NGFGUs.

(3) To confirm the model's efficacy, two case studies are conducted. The outcomes demonstrate that the P2G procedure is successful in increasing the rate at which wind energy is utilised. It has also been demonstrated that the P2G method can help cut down on natural gas use and emissions.

The role of energy storage in system operation is becoming more and more crucial. Future research could examine the effects of both electrical and gas energy storage on the performance of integrated gas-electric energy systems.

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