Effect of P2G on Suppression of New Energy Fluctuations and Carbon Capture and Dynamic Simulation of Gas Pipeline

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ABSTRACT: The rise of power-to-gas (P2G) technology provides an effective way for the absorption of low-carbon intermittent energy sources such as wind energy and photovoltaics. At the same time, the application and promotion of power-to-gas (P2G) are beneficial to the realization of carbon-neutral goals and realize carbon recycling. This paper analyzes the principle of the power-to-gas process, including the two steps of power-to-hydrogen (P2H) and methanation, and analyzes how to use a power-to-gas facility to increase the grid-connected ratio of new energy power generation and alleviate wind and solar abandonment. This paper proposed a solution to the above problem, and analyzed the effect of power-to-gas on carbon capture, at the same time calculated the number of carbon emissions that can be reduced in the unit of energy produced, and finally, we can conclude that power-to-gas is effective in stabilizing new energy volatility and carbon neutrality and have significant social benefits and economic value. The main component of natural gas is methane, so the methane produced by P2G can be directly injected into the natural gas pipeline. Since the rate of methane production fluctuates frequently. Therefore, it will cause frequent fluctuations of the gas in the pipeline, which may cause the gas pressure, flow, and pipeline pack to exceed the limitation. This paper uses the method of characteristic to solve the differential equation of the pipeline to analyze the dynamic fluctuation process of pressure, flow rate, and pipeline-pack, and finally compared with thermodynamic calculation to verify the correctness of the algorithm.

1. Introduction

Energy is the foundation for human survival and development and the lifeblood of the national economy. How to reduce environmental pollution in the process of energy consumption while ensuring the sustainable supply of energy for human society is a hot spot of common concern for all countries in the world today [1]. At present, in the production activities of human society, coal, oil, and natural gas are still the main sources of energy supply. With the rapid growth of energy consumption and the massive use of fossil fuels, resource depletion and environmental pollution are threatening the global ecology. Therefore, improving energy efficiency, exploring new energy sources, and realizing large-scale development of renewable energy has become the inevitable choice to solve the increasingly prominent conflicts between energy demand growth and energy shortage, energy utilization, and environmental protection in the development of human society. Solve the bottleneck of high-proportion consumption of new energy, promote the clean energy structure and increase the utilization rate of energy consumption terminals, and realize the transformation and upgrading of the energy system have been upgraded to the national strategy of energy revolution[2][3]. New energy power generation technologies such as wind power and photovoltaics are relatively mature, but their inherent randomness and
intermittentness pose challenges to the security and stability of the grid and operation scheduling. The problem of wind curtailment and solar curtailment is serious, which restricts the large-scale application of new energy power generation. Energy storage systems are required to smooth the output of new energy power generation. The existing energy storage methods include electric boilers, pumped storage, flywheel energy storage, seawater desalination, etc. These methods cannot be applied on a large scale due to their small storage capacity, low efficiency, insufficient long-term effective energy storage, and a large investment.

Power-to-gas (P2G) technology can realize the conversion of energy from power systems to hydrogen and natural gas systems, and realize large-scale and long-term storage and transportation of electric energy, and realize the space-time transfer of electric energy. Compared with traditional energy storage methods, it has great advantages[4][5]. In addition, P2G technology makes the energy flow between the power system and the natural gas system change from one-way to two-way, and it can realize the mutual conversion of electric power and natural gas, help realize the integration of multiple energy systems, and strengthen the effective interaction between energy resources. The literature [6] proves the effect of P2G on the absorption of intermittent new energy through the analysis of the optimal scheduling model of the integrated energy system including P2G. Literature [7-9] proposes that P2G technology can play a great role in the background of a high percentage of new energy penetration and low carbon requirements. After the large-scale integration of wind power, the uncertainty of its output poses a great challenge to the safe operation of the power grid, which requires the power grid to reserve more spinning reserve capacity which reduces the economics of operation. We can use excess new energy to generate methane by P2G equipment. Since 97% of natural gas is methane, methane can be directly injected into natural gas pipelines without the need to increase additional investment in the construction of gas storage equipment, which greatly reduces the cost. At the same time, a large amount of carbon is absorbed in the process of methanation, which can realize carbon recovery and reduce carbon emissions.

Injecting the produced methane by P2G directly into natural gas pipelines reduced the investment in the construction of gas storage facilities, which will convert the volatility of intermittent new energy power generation into gas fluctuations in the gas pipeline, and it may cause over-limitation problems in pressure, flow rate, and pipeline storage. The stable power supply of the gas turbine relies on the stable gas supply of the pipeline, so the over-limitation problem may cause the unstable operation of the gas turbine, which will affect the power system. Dynamic simulation of the generated fluctuations was carried out through the written simulation program and the reasonableness of the calculation results was verified by comparing with the thermodynamic calculation results.

This paper analyzed the cost of P2G gas production, steps of P2G, the effect of P2G carbon absorption, and the smoothing effect of P2G on the fluctuation of new energy power generation, and proposed a control strategy for suppressing the fluctuation of new energy power generation. The control strategy can increase the proportion of new energy power generation connected to the power grid, and can increase the reputation of new energy power plants, thereby bringing economic and social benefits to the power plants; After that, a simulation program was written to simulate the dynamic fluctuations of gas pressure, flow, and storage in the pipeline network due to the unstable injection rate of methane. Through the dynamic simulation curve, it is possible to clarify whether each component and pipeline is safe to operate and the extent of the over-limitation component, which can provide technical support for the planning of the integrated energy system, accurately calculate the operating boundary for checking calculations, improve the economy of the integrated energy system, and promote the development of the integrated energy system.

2. Overview of P2G

China is committed to working hard to achieve the goal of carbon neutrality by 2060 and respond to international climate change. The application of P2G technology can play an important and positive role in the process of achieving carbon neutrality and energy conservation and emission reduction goals. This section analyzes the cost of P2G and the principle of procedures of P2G.
2.1 The cost of P2G

First of all, P2G is feasible in principle and technology. There are many P2G demonstration bases in Germany, but the overall efficiency (about 60%) is low, which limited its large-scale promotion and application. Comprehensive static analysis shows that the natural gas produced directly from industrial electricity to produce gas is at least about three times the market price, of which electricity price and the cost of P2G devices are the main influencing factors. The procedure that can be improved now is the P2G device, which can improve the efficiency of P2G by adopting new technologies and new management strategies, and reduce the cost by increasing the scale of the P2G device.

The investment of P2G is still relatively high. If a third-party company is used as the main investment and operation entity, it will face problems such as large investment in site selection and construction and difficulty in cost recovery [10]. In order to promote P2G technology better, it cannot simply be compared with the price of natural gas in the market. It is necessary to consider the economic benefits brought by carbon trading, the economic benefits brought by increasing the proportion of new energy power generation into the power grid, and the social benefits brought about by promoting the national carbon-neutral target, and so on. Therefore, in addition to direct energy sales revenue, P2G technology can also provide auxiliary services such as backup and carbon capture for the system, thereby bringing auxiliary service benefits. Germany has already applied P2G technology to practice and completed a pilot P2G plant in 2012 [11].

In the integrated energy system, the coupling link between the power grid and the natural gas network is a gas turbine, however, gas turbines can only achieve its unidirectional coupling, so P2G is a key technical link in building a comprehensive energy system to realize the conversion of electricity to gas, which achieved the bidirectional coupling and improved the stability and efficiency of the integrated energy system. To realize the large-scale application of P2G, the benefits of P2G must be comprehensively considered.

2.2 Analysis of the principles and procedures of P2G

P2G production includes two procedures, namely hydrogen production, and methanation. Among them, the efficiency of hydrogen production by electricity has different efficiencies due to different methods. The efficiency range is 65%-81%. After methanation, the efficiency will continue to decrease to 54%-65%. However, the reduction in efficiency can be compensated by using the energy generated by hydrogen combustion. The schematic diagram is shown in Figure 1.

![Fig 1 Schematic diagram of P2G](image)

The electrolysis of water and methanation are represented by the following equations:

\[
\begin{align*}
H_2O & \rightarrow H_2 + \frac{1}{2}O_2 \\
4H_2 + CO_2 & \rightarrow CH_4 + 2H_2O
\end{align*}
\]

Common water electrolysis technologies include Alkaline Water Electrolysis (AWE), Proton Exchange Membrane Electrolysis (PEME), Solid oxide electrolysis cell (SOEC), High-Temperature Electrolysis (HTE), etc. AWE hydrogen production is the most mature and low-cost large-scale...
hydrogen production method. The purity of hydrogen and oxygen produced can generally reach 99.9%, but the startup time is slow, and there is no way to track and absorb the fluctuations of new energy power generation in time; PEME uses solid Polymer membranes to replace traditional electrolytes, with low operating temperature, short cold start and adjustment time, fast response speed, and high overall efficiency. However, the overall scale and life expectancy need to be improved; The efficiency of SOEC electrolysis of high-temperature water vapor has been improved, but high-temperature water vapor requires additional energy supply, and a small amount of water vapor is mixed in the gas produced. The overall economy is not improved. The start-up adjustment time is yet to be studied; The working temperature of HTE hydrogen production is about 800–950°C. High temperature not only improves the efficiency of electrolysis, at the same time limits the choice of key materials for the electrolytic cell. The high-temperature environment has higher requirements for materials, sealing, and assembly.

For the second step of P2G methanation, there are mainly two technical methods: Chemical Methanation (CM) and Bio-methanation (BM). At this stage, the methanation technology based on CM has high conversion efficiency and excellent economies of scale. It has been commercialized. The efficiency of BM methanation technology is higher than that of CM, but the capacity is KW, which is not suitable for large-scale applications and is in the preparation stage for commercialization.

3. The effect on carbon absorption by P2G

3.1 Schematic diagram of the carbon cycle

P2G includes two steps. The methanation process needs to consume carbon dioxide, which can reduce carbon dioxide emissions and realize carbon recycling. The schematic diagram is shown in Figure 2.

![Fig 2 Schematic diagram of P2G carbon recycling](image)

3.2 P2G carbon capture calculation

The combustion heat value of methane is 0.0153Mwh/kg. Each kilogram of methane combustion can produce 0.0153Mwh of energy, and 1/0.0153=65.36kg of methane is required to produce 1Mwh of energy.

According to the chemical equation of methanation:

$$4H_2 + CO_2 \Rightarrow CH_4 + 2H_2O$$

It is calculated that the amount of carbon dioxide required is: 65.36*44/16=180kg, so the methane with 1Mwh energy produced through the entire process of producing methane by electricity can reduce carbon emissions by 180kg, basically achieving the goal of carbon neutrality.

4. The strategies of using P2G and gas turbines to stabilize new energy fluctuation

It is widely regarded as the most suitable application scenario for P2G technology to absorb the surplus power generation output of intermittent renewable energy and alleviate the fluctuation of renewable energy power generation output [12].
Since wind power, photovoltaics, and other renewable energy generation have the characteristics of anti-peak shaving, this characteristic will cause difficulties in the absorption of new energy, and a control strategy is proposed to achieve the goal of smoothing the intermittent energy generation curve and improving the grid utilization rate by utilizing the energy conversion and space-time translation characteristics of P2G and the rapid adjustment capability of gas turbines.

P2G equipment needs to consume electric energy during operation. If the P2G equipment is put into operation during the period when the electric load is low and wind power is high, it is equivalent to increasing the electric load of the system, which plays a role of "filling the valley" for the electric load and plays a role of "peak shaving" for renewable energy power generation. At the same time, the gas produced by electricity generation gas is injected into the gas pipeline to supply gas to the gas turbine for power generation. At the same time, the gas produced by electricity generation is injected into the gas pipeline to supply gas to the gas turbine for power generation, which can play a role of "filling the valley" in the low valley of new energy power generation. This can improve the security of renewable energy and increase the consumption of new energy.

![Fig 3 Schematic diagram of P2G and gas turbines utilizing renewable energy fluctuations](image)

This strategy uses the power control mode, as shown in Figure 3. Track the offset of intermittent energy generation and the power of a given grid curve, and control the output power of P2G and gas turbines. The control strategy is set as follows: P2G equipment can be turned off when the new energy power generation is low, and the gas turbine responds quickly to increase the output, to fill in the trough of the output of new energy power generation; When the new energy power generation is high, we could turn off the gas turbine and turn on the P2G equipment to consume the excess new energy power generation through the P2G equipment and cut the peak of the power generation, which can achieve the goal of stabilizing the new energy power generation.

5. Other P2G application scenarios
According to published papers at home and abroad, it can be concluded that P2G technology can not only be used as a method of large-capacity energy storage to absorb surplus intermittent energy generation, but also can participate in system frequency modulation and peak regulation, and provide system backup, participating in the optimized operation of the power system, participating in the coordination and optimization of multi-energy systems such as electricity-gas-heating-cold, participating in the operation of the intelligent transportation system, and alleviating the problem of power/natural gas network congestion.
6. Simulation Case

Fig 4 Topology diagram of integrated energy system

In this calculation case, there are 5 nodes. The arrow pointing to the node represents the input gas, and the node pointing to the outside is the output gas. Node 1 is the injection node of methane produced by P2G, nodes 2 and 4 are gas turbines, and node 3 is a branch node, and node 5 is a stable gas source. The parameters of the system are shown in Table 1. The given initial values and the initial values obtained by power flow calculation are shown in tables 2 and tables 3.

Table 1 Parameter values of integrated energy system

| Symbol | Content              | Value    |
|-------|----------------------|----------|
| L_{13} | Length of pipeline   | 2000m    |
| L_{32} | Length of pipeline   | 1200m    |
| L_{34} | Length of pipeline   | 2400m    |
| L_{45} | Length of pipeline   | 2800m    |
| L_{51} | Length of pipeline   | 1600m    |
| D_{13} | Diameter of pipeline | 490mm    |
| D_{32} | Diameter of pipeline | 490mm    |
| D_{34} | Diameter of pipeline | 300mm    |
| D_{45} | Diameter of pipeline | 300mm    |
| D_{51} | Diameter of pipeline | 300mm    |
| T     | Constant temperature | 293K     |
| a     | Speed of sound       | 400m/s   |
| K     | Absolute roughness   | 0.04mm   |
| v     | Dynamic viscosity coefficient | 1.156×10^{-5}Pa·s |
| g     | Acceleration of gravity | 9.8m/s² |
| Z     | Compressibility factor | 0.98    |
| R     | Ideal gas constant   | 557.22J/(kg·K⁻¹) |
| Δx    | Space step           | 400m     |
| Δt    | Time Step            | 1s       |

Table 2 Initial value of node pressure

| Node | Pressure(MPa) |
|------|---------------|
| 1    | 3.900000      |
| 2    | 3.810175      |
| 3    | 3.837300      |
| 4    | 3.820978      |
| 5    | 3.899994      |
Table 3 Initial value of node flow rate

| Entry node | Exit node | Flow rate (kg/s) |
|------------|-----------|-----------------|
| 1          | 3         | 47.455436       |
| 3          | 2         | 40.000000       |
| 1          | 5         | 2.544564        |
| 5          | 4         | 12.544564       |
| 3          | 4         | 7.455436        |

The disturbance of the system is set as a step mutation of the pressure of the corresponding node of the P2G. The interference settings are as follows: at 0s, the methane produced by the large-scale P2G production equipment is directly injected into the natural gas pipeline from node 1, and the initial pressure formed is 3.90MPA. Because the output of new energy increases, the pressure of node 1 rises to 3.95MPa at 1s. The pressure at node 1 rose to 3.99MPa at 10s. The simulation time is 40s, the time step is set to 1s, and the distance step is 400m which is obtained according to the characteristic line constraint equation.

The dynamic simulation of the pipeline connecting node 1 and node 3 was carried out, and the length of the pipeline is 2000m, the distance step is 400m, and it is divided into 5 sections. The connection point of the divided pipe element is defined as a virtual node, namely node 1, 2, 3, 4, So there are 6 computing nodes (including virtual nodes), as shown in Figure 5.

Fig 5 Schematic diagram of pipeline nodes

Analyze the pressure and flow of 6 nodes (including virtual nodes) and the storage of pipelines connecting node 1 and node 3. The simulation results are as follows:

Fig 6 The pressure curve of different nodes of the pipeline with time

The propagation speed of the pressure wave is the speed of sound, which is 400m per second in this simulation calculation. As the P2G device adjusts the given input at node 0, it can be seen that it is a disturbance of two steps. From the simulation graph, it can be seen that node 1, node 2, node 3, node 4, and node 5 are all delayed by 1s from the previous node. This is because the distance step is 400m, and the set speed of sound is also 400 meters per second, and the pressure wave is also 400 meters per second, so the correctness of the simulation can be verified; The pressure wave changes regularly before it is reflected in the pipe network, and the obvious translation characteristics can be seen from the graph. After the reflection of the pressure wave occurs, that is, after 15 seconds, the pressure curve begins to change irregularly. This is because of the superposition of various pressure waves. It can also be known...
from the curve that the maximum pressure does not appear at the entrance of node 0 of the pipeline, but at node 1, so that the upper and lower limits of pressure can be grasped more accurately.

Due to the compressibility of the gas, the flow rate of the gas at different locations in the pipeline at the same time is different, and even reverse flow will occur, which will cause the problem of pipe bursting. Before the reflected wave appears, there are also obvious delays between different nodes. After 15 seconds, the appearance of the reflected wave makes the flow curves of different nodes become disorderly and affects the gas supply of the connected gas load.

Linepack is the key to transforming rigid fluctuations of electricity into flexible fluctuations of gas. Adequate gas storage can reduce frequent operations of valves and switches, so it is an important indicator in the natural gas system. Through the dynamic simulation curve, the amount of natural gas stored in the pipeline at any time can be known, so as to guide the optimized operation of the integrated energy system.

In summary, the dynamic simulation of the natural gas network in the integrated energy system through a simulation platform based on the characteristic line method can improve the economic operation level of the integrated energy system, save operating costs, and improve the reliability of energy supply, which has a strong practical significance.

7. Conclusion
This paper analyzes the cost of P2G, the steps of P2G, the carbon absorption effect by P2G, and the effect on the fluctuation of new energy power generation by P2G. It is concluded that: only considering the cost of P2G, P2G technology is not competitive. It must integrate social benefits and other factors to improve the competitiveness of P2G; For electric hydrogen production and methanation, considering
factors such as economics, technological maturity, and sensitivity, selecting PEME electric hydrogen production technology and CM methanation technology can achieve optimal results; By analyzing the carbon capture capability of P2G, it can be concluded that P2G can provide strong support for the country to achieve the goal of carbon neutrality; This paper proposes a model for the joint operation of gas turbines and P2G equipment. By setting control strategies, the goal of suppressing the volatility of new energy power generation can be achieved; The paper summarized the possible application scenarios of P2G technology in the future according to relevant literature. Through the compiled dynamic simulation program, the process of dynamic fluctuation of gas in the natural gas pipeline network caused by the absorption of new energy power generation is simulated, and the operation boundary of the natural gas system in the integrated energy system is clearly grasped, providing technical support for the economic operation optimization and control strategy of the integrated energy system.

In summary, P2G equipment can effectively promote new energy consumption and improve the environmental benefits of system operation. As China's requirements for clean energy and low-carbonization become higher and higher, P2G technology is expected to play an important role in the integrated energy Internet and has a very broad development prospect and application range. With the advancement of technology, the design capacity of P2G projects will gradually increase, which will have an increasingly obvious impact on the operation of power systems and natural gas systems. Future work needs to analyze the impact of large-scale P2G equipment connected to the power grid and natural gas network on their network security and the possible cascading failures, and a platform suitable for dynamic simulation of integrated energy systems needs to be established.

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Acknowledgments

This article is one of the phased achievements of the national key R&D project "Research on key technologies of the multi-energy complementary new energy system for cross-border interconnection" (2018YFE0208400).

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