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Energy saving and environmental protection in coupled development of integrated gas-electric system: from the perspective of gas pipe network planning

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ABSTRACT

With the development and popularization of gas-fired power generation and P2G technology, the electrical system is becoming more and more closely connected. Gas energy is a good form of energy storage or transition in integrated energy system. However, few theoretical studies conduct on the coupling development of gas network and integrated energy network from the perspective of natural gas network planning. Improper natural gas system infrastructure planning will lead to waste of resources and environmental impact. Therefore, this paper aims to improve the efficiency of gas transport from the perspective of gas pipeline network planning and promote the development of low carbon economic coupling of gas integrated system (IGES). We propose a multi-dimensional natural gas network system planning strategy that enhances the link between it and electrical system to solve how to convey natural gas from P2G station into pipelines. The strategy simulates the planning behavior of natural gas pipeline network company under the background of integrated electricity and gas system and analyzes the economic and environmental benefits of the new strategy. The results show that a feasible planning scheme can improve the economic benefits of gas network operators and reduce the carbon emissions. Based on these analyses and conclusions, recommendations are made for policy formulation and planning directions at different levels. In summary, the new gas pipe network planning strategy will help to enhance the importance of gas pipe network in the IGES and promote energy conservation and environmental protection in the energy industry.

Keywords: Gas pipe network planning, Economy, Carbon emissions, Gas-electric coupling development

1. INTRODUCTION

1.1 Background

With the development of gas-fired power plants and the rise of P2G technology, the coupling of gas-electricity system is becoming closer and closer, which is a good way to alleviate environmental degradation [1] and the imbalance of energy supply and demand [2]. In particular, P2G technology can not only alleviate the phenomenon of wind and light abandonment in power system but also promote the popularization of CCUS by using CO2, and increase the income of the natural gas pipeline company, which realize a win-win situation. The planning of integrated gas-electric system (IGES) and the construction of P2G station are undertaken by many related parties. Due to its high investment cost, the construction progress is slow, which affects the development of IGES. Therefore, the P2G station gas storage facilities and special gas transmission pipeline planning is researched from the prospective of natural gas pipeline network in this paper.

1.2 Related work

For the planning and construction of IGES, scholars have mainly studied to optimize the overall social interest. Sequential distributed approach [3-4] and two-stage stochastic optimization [5] are used to realize the cooperative planning of the IGES, but for the natural gas pipeline network company, which often bears most of the construction costs, and the income from storage and

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transmission of the newly built facilities also accounts for a large portion of the overall revenue, which results in the difficulty of evaluating the investment planning scheme from the perspective of natural gas company

To address the above problems, researchers consider the independent benefits of the power system and the natural gas system, as well as the impact of the natural gas price on the planning results [6-7]. However, the above studies have not involved the infrastructure construction costs and revenues of the dedicated pipelines at P2G stations and gas storage facilities. The construction of gas storage facilities cost a lot, but there is a lack of corresponding price guidance [8-9] and investment recovery mechanism [10-11], which leads to low motivation of natural gas company in investment construction. Hence, how to transport the natural gas generated by P2G to the natural gas pipeline network economically and rationally, and how to plan and construct this part of infrastructure reasonably are the key points of this paper.

2. MATHEMATICAL MODEL

In the coupling development of the electrical network, the gas power plant and the P2G station are the key to connecting the two different energy networks. The gas power plant provides a certain amount of electricity to the power grid through natural gas power generation, and the P2G station converts the excess electricity into gas energy and injects it into the natural gas pipeline network system. How to input the natural gas generated by P2G into the natural gas pipeline network, and how much capacity the natural gas company can build energy storage equipment and natural gas pipeline is an economical and reasonable issue. Next, the objective function and constraints of the model are described in detail.

2.1 Objective function

2.2.1 Maximize the operating profit of natural gas pipeline network

$$E = E_{pipe} + E_{sto} - \left(C_{comp} + C_{pipe} + C_{sto}\right) \tag{1}$$

The revenue of natural gas pipeline network is related to pipeline gas transmission revenue E_{pipe}, gas storage revenue E_{sto}, compressor station cost C_{comp}, pipeline construction cost C_{pipe} and gas storage construction cost E_{sto}.

2.2.2 The electrical integrated network has the lowest carbon emissions

$$F = F_{coal} + F_{gas} + F_{comp} + M \cdot \left(P^{dem} - P^{coal} - P^{gas} - P^{renew}\right) \tag{2}$$

Carbon emissions mainly include coal power generation emissions F_{coal}, gas power generation emissions, compressor station emissions and carbon emission compensation caused by insufficient natural gas power generation, M is the compensation coefficient.

2.2 Constraints

2.2.3 Natural gas pipeline network constraints

The frequent occurrences of sets and variables in constraints are explained as follows: Ω represent the set of all nodes in a pipeline network topology diagram, including source nodes, sink nodes, compressor station nodes, and ordinary nodes; Ψ represent the set of all pipelines in a pipeline network topology, including built pipelines, possibly new pipelines; Ψ_{exist} represent the set of existing pipelines; Ψ_{new} represent the set of possibly existing pipelines; T represent the set of time periods; H represent the set of new pipeline diameter specifications; G represent the set of pressurization types of the compressor station; In represent the set of incoming arcs indicates natural gas flows from pipeline p into node i; Ou represent the set of outgoing arcs indicates natural gas flows from node i into pipeline p; Φ represent pipeline flow, 10^8m^3; $\Phi^{down}_{i,t}$ represent the gas volume downloaded, 10^8m^3; $\Phi^{up}_{i,t}$ represent the gas volume uploaded, 10^8m^3; B represents a large number;

Flow constraint of natural gas pipeline network:

$$\Phi^{up}_{i,t} + \sum_{(j,i,p)\in\Psi} \Phi_{j,i,p,t} = \sum_{(i,j,p)\in\Psi} \Phi_{i,j,p,t} + \Phi^{down}_{i,t}, \forall t \in T \tag{3}$$

$$\Phi^{up}_{i,t} \le s_{i,t} \quad \forall i \in \Omega_{sup}, \forall t \in T \tag{4}$$

$$\Phi^{down}_{i,t} \ge d_{i,t} \quad \forall i \in \Omega_{dem}, \forall t \in T \tag{5}$$

Where Ω_{sup} represent the set of all source nodes in a pipeline network topology; Ω_{dem} represent the set of all sink nodes in the pipeline network topology; Ω_{comp} represent the set of all compressor station nodes with pressurization function in a pipeline network topology.

Structural constraints of natural gas pipeline network:

$$N_{p,t} = \alpha_p \quad \forall (i,j,p) \in \Psi, t=0 \tag{6}$$

$$N_{p,t} \le \sum_{h\in H}\sum_{0}^{t} M_{p,h,t} + \alpha_p \quad \forall (i,j,p) \in \Psi, \forall t \in T \tag{7}$$

$$N_{p,t} \le N_{p,t+1} \quad \forall (i,j,p) \in \Psi, \forall t \in \{0,1,\ldots,|T|-1\} \tag{8}$$

Where $N_{p,t}$ represent if pipeline p exists in period t; $M_{p,h,t}$ represent if the pipeline waiting to be built; α_p represent the pipeline capacity;

Pipeline transport capacity constraints:

$$I_{p,t} = \beta_p \quad \forall (i,j,p) \in (\Psi - \Psi_{new}), \forall t \in T \tag{9}$$

$$I_{p,t} = 0 \quad \forall (i,j,p) \in \Psi_{new}, t \in \{1,2,\ldots,\lambda\} \tag{10}$$

$$I^{add}_{p,t} = \sum_{t'\in 1,2,...,t}\sum_{h\in H} q_d^{cons}\cdot M_{p,h,t'}\ \forall(i,j,p)\in\Psi_{new},\forall t\in\{1,...,|T|\} \quad (11)$$

$$N_{p,t}=N_{p,0}+N^{add}_{p,t-\lambda},\forall(i,j,p)\in\Psi_{new},\forall t\in\{\lambda,...,|T|\} \quad (12)$$

$$\Phi_{i,j,p,t}\le I_{p,t}\quad \forall(i,j,p)\in\Psi,t\in T \quad (13)$$

Where θ_p represent the transport capacity of pipeline p, $10^8 m^3$; $I_{p,t}$ represent the transport capacity, $10^8 m^3$; $I^{add}_{p,t}$ represent The increased delivery capacity of pipeline p, $10^8 m^3$;

Gas storage constraints：

$$\theta_i^{min}\le K_{i,t}\le\theta_i^{max}, i\in\Omega_{stor},t\in T \quad (14)$$

$$\Phi^{up}_{i,t}-\Phi^{down}_{i,t}=K_{i,t}-K_{i,t-1}, i\in\Omega_{stor}, t\in T, t\ne 0 \quad (15)$$

Where Ω_{stor} represent the set of all gas storage nodes in a pipeline network topology; $K_{i,t}$ represent the gas storage , $10^8 m^3$; ϑ^{min}_i represent the minimum capacity, $10^8 m^3$; ϑ^{max}_i represent the maximum capacity , $10^8 m^3$;

Pipe pressure constraints：

$$\Psi^2_{i,p,t}=(\Psi^2_{j,p,t}+\sigma_p\cdot\Phi^2_{i,j,p,t}),\forall(i,j,p)\in\Psi,t\in T \quad (16)$$

$$\Psi_{i,p,t}\ge\psi_p^{min}+B\cdot(\Lambda_{i,j,t}-1),\forall(i,j,p)\in\Psi_{exist},(i,p)\in In,t\in T \quad (17)$$

$$\Psi_{i,p,t}\le\psi_p^{max},\forall(i,j,p)\in\Psi_{exist},t\in T \quad (18)$$

$$\psi^{min}_{p,h}\le\psi_{i,p,t}\le\psi^{max}_{p,h},(i,j,p)\in\Psi_{new},h\in E \quad (19)$$

Where Ψ represent the set of all pipelines in a pipeline network topology, including built pipelines, possibly new pipelines; Ψ_{exist} represent the set of existing pipelines, MPa; Ψ_{new} represent the set of possibly existing pipelines, MPa; ψ_i^{min} represent the lower pressure limit of node i, MPa; ψ_i^{max} represent the upper pressure limit of node i, MPa; σ_p represent hydraulic coefficient;

2.2.4 electric network generation constraints

In the peak season of electricity consumption, the power generation will not exceed the total demand for electricity, while there is a surplus of electricity in the off-season; α_{g2p} is the power generation coefficient of natural gas; α_{p2g} is gas production coefficient of P2G.

$$coal_t^{power}+gas_t^{power}+renew_t^{power}\le dem_t^{power} \quad (20)$$

$$po_t^{remain}=coal_t^{power}+renew_t^{power}-dem_t^{power} \quad (21)$$

The power generation of gas turbine is related to the amount of natural gas flowing into the node.

$$po^{gas}_{i,t}\le\alpha_{p2g}\cdot Q^{do}_{i,t}, i\in N_{G2P} \quad (22)$$

The gas production of P2G station Po^{P2G} is related to the excess power po^{remian}. The amount of natural gas uploaded by P2G station is subject to the gas storage capacity V and gas production of P2G station.

$$Po^{P2G}_{i,t}\le\alpha_{p2g}\cdot po^{remain}_{i,t}, i\in N_{P2G} \quad (23)$$

$$\Phi^{up}_{i,t}+V_{i,t}-V_{i,t-1}\le Power^{P2G}_{i,t}, i\in N_{P2G}, t=2,3,...,T \quad (24)$$

$$\Phi^{up}_{i,t}+V_{i,t}\le Po^{P2G}_{i,t}, i\in N_{P2G}, t=1 \quad (25)$$

$$V_{i,t}\le\sum_r BS_{i,r}\cdot v_r+v, i\in N_{P2G},t\in T \quad (26)$$

V indicates the gas storage capacity of the gas storage facility, and BS indicates whether to build gas storage facility.

3. CASE STUDY

Based on the above-mentioned electrical integrated network planning optimization model from the perspective of natural gas operators, this section plans the gas storage facilities and dedicated gas pipelines of P2G stations. The proposed model is programmed in Python language, and the efficient solver Gurobi is called to solve the optimization model. The model runs on a computer with AMD Ryzen 7 5800H (3.20 GHz) and 16 GB memory. Based on the improved IEEE13 node example, the network structure includes 8 nodes in the natural gas pipeline network, including gas suppliers, compressor stations, gas storages, ordinary distribution stations, P2G stations, gas-fired power plants and other natural gas customers, including 5 pipelines with different transmission capacities.

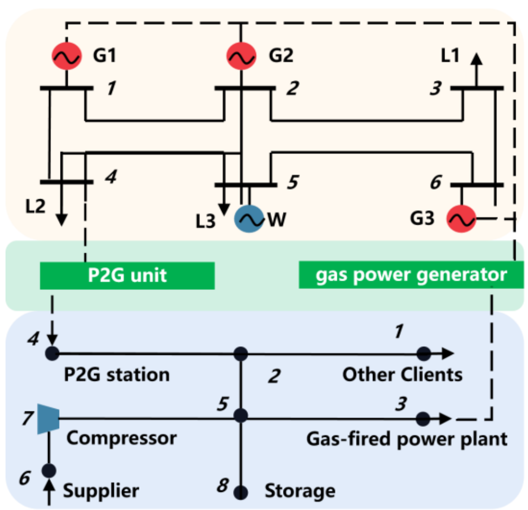

Fig. 1. IGES structure diagram

In this study, the energy demand is used to distinguish the off-season and peak season periods. The forecasts of electricity demand, renewable power generation, natural gas demand and natural gas supply in 24 periods are shown in Fig. 2. Both natural gas demand and electricity demand show a fluctuating upward trend, while the domestic natural gas supply capacity is growing slowly and limited. New energy sources such as P2G are growing rapidly, but the peak season period of renewable power generation is often in the off-season, which is opposite to the trend of electricity demand. Therefore, there is a problem of unbalanced power consumption and power generation time in the electric network. The sample scenarios are not based on field data but are designed to illustrate functionality.

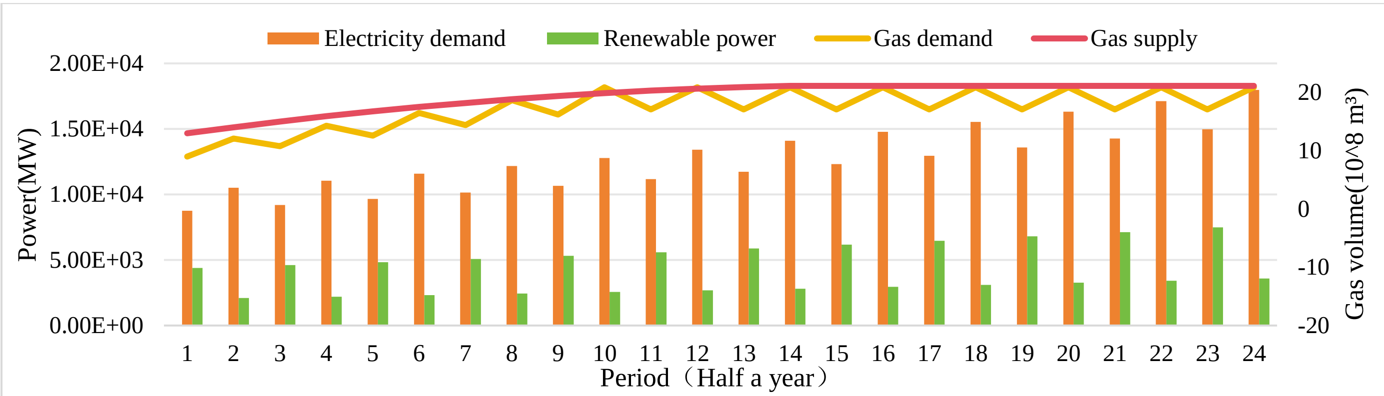

Fig. 2. Forecasts of electricity demand, renewable power generation, natural gas demand and natural gas supply for 24 periods

3.1 Case one

The energy generation and total carbon emissions without planning and construction of the natural gas pipeline network system are shown in Fig. 3. With the change of electricity demand and the proportion of different energy power generation, the carbon emissions of the system are also changing, showing a regular fluctuation trend. In the off-season of electricity demand, renewable energy resources are relatively abundant, and the power generation capacity is large, but the electricity resources cannot be stored on a large scale. Therefore, this part of electric energy can be converted into gas energy input into the natural gas pipeline network system through the P2G device and stored. In the peak season of electricity demand, natural gas power generation is increased, which solves the instability of renewable energy power generation to a certain extent and meets the needs of electric peak shaving.

It can be seen from Fig. 4 that due to the limited gas transmission and storage capacity of natural gas pipelines and gas storage facilities, there is a problem that excess power resources cannot be completely consumed, and with the increase of surplus power in the off-season, more power is wasted. In this scenario, the gas storage facilities of the P2G station have reached the maximum storage capacity. At the same time, the pipeline transported from the P2G station to the pipe network system is also at full load during the peak season, and it has been unable to absorb excess electricity. Therefore, we can imagine that if it is not limited by the gas storage and transmission capacity of the natural gas pipeline network infrastructure, the gas network can better absorb the excess energy of the electric network, and can also provide more natural gas to the gas-fired power plant during the peak season of electricity demand.

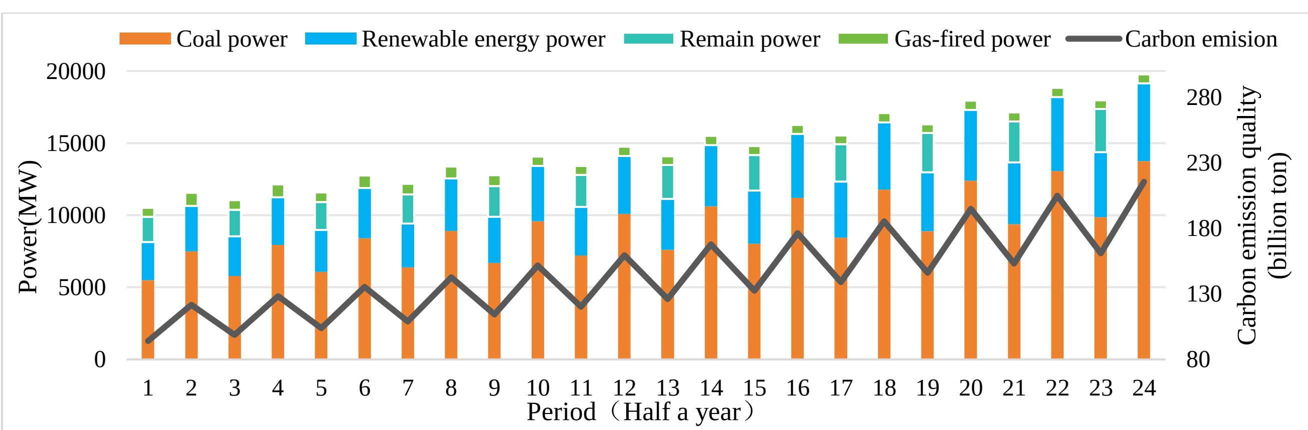

Fig. 3. Energy generation and total carbon emissions without planning and construction per period

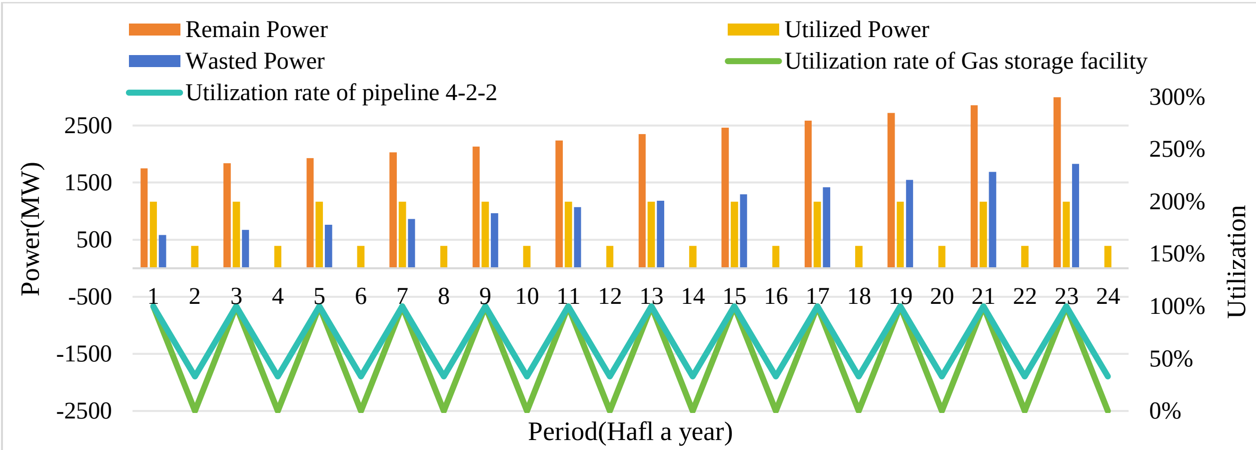

Fig. 4. Utilization and waste of excess power and the load of gas storage facilities and P2G dedicated pipelines in the corresponding period

3.2 Case two

Table. 1 Economic and environmental analysis of natural gas pipeline network system after facility planning

scenario	case 1	case 2	unit
Planned construction results	/	Pipeline: 600 million cubic meters / year Gas storage facilities: 500 million cubic meters	/
Total profit	1, 390.3	**1, 443.9**	Million CNY
Pipeline transmission profit	1, 384.3	1, 443.9	Million CNY
Gas storage profit	6	65	Million CNY
Pipeline construction cost	/	15	Million CNY
Gas storage construction cost	/	50	Million CNY
Carbon emissions	3, 419.41	**3, 389.39**	Bilion ton
Total coal power generation	903.63	888.12	TWh
Total renewable energy generation	433.34	433.34	TWh
Total natural gas power generation	68.45	**83.95**	TWh

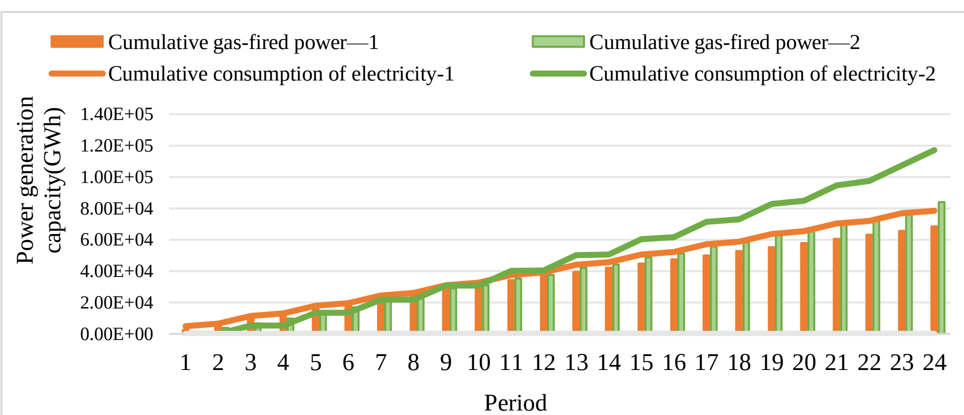

Fig. 5. Cumulative gas power generation and electricity consumption in different scenarios

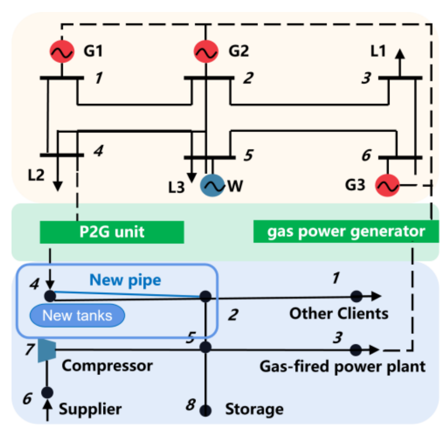

Fig. 6. Electric integrated energy network planning scheme

After the natural gas pipeline network system planning, the natural gas pipeline network operation company has obtained more profits, as shown in Table. 1. In scenario 2, the planning model decided to build 600 million cubic meters / year pipelines and 500 million cubic meters gas storage facilities (Fig. 6). Although the investment in pipeline and gas storage facilities has paid a huge cost, it has been compensated for the pipeline and gas storage profits. In general, the profit of natural gas companies has increased by 53.62 Million RMB, reaching 3.86%. On the other hand, infrastructure construction has improved the gas transmission capacity between the P2G station and the pipeline network system and its gas storage capacity, allowing the natural gas pipeline network to absorb more power resources and transport more gas resources. In addition, the total amount of natural gas power generation is increased, and the proportion of natural gas power generation in the power grid is increased from 5.31% to 6.51%, reducing more than 30 billion tons of carbon emissions. In summary, the natural gas pipeline network system planning scheme can not only reduce the waste of electric energy, but also improve the power generation structure of different energy sources.

4. CONCLUSIONS

From the perspective of natural gas companies, this paper establishes a small connection part of the electrical integrated energy network — the gas storage facilities and special pipeline planning model of P2G station yard, and proposes an economic and environmental planning scheme for the coupling development of natural gas pipeline network companies in the gas-electric integrated energy network.

Appropriate P2G station gas storage facilities and special pipeline planning schemes can effectively improve the profit of natural gas pipeline network companies, and can consume excess electricity to a greater extent to convert it into gas energy for storage or transportation. While reducing the overall energy waste, it can also increase the proportion of natural gas power generation, and reduce carbon emissions to make a certain contribution to the protection of the environment.

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