The Construction of the Integrated Energy Planning Mathematical Model of Dynamic Natural Gas-Electricity Coupling

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Abstract. To rationally utilize the energy and reduce the energy consumption and environmental pollution as much as possible while meeting the power demands, the mathematical planning method is used to construct an integrated energy planning mathematical (EPM) model of natural gas-electricity coupling, thereby achieving the optimal planning of energy. The research results show that the integrated energy planning model constructed by mathematical planning method has excellent adaptability, which can meet the needs of energy conservation and environmental protection. Therefore, the construction of an integrated EPM of dynamic natural gas-electricity coupling is of practical significance for the rational utilization of energy resources and the protection of the environment.

Keywords: Natural gas, electric power, coupling, energy planning.

1. Introduction
Energy resource is an important material basis for the survival and development of human society. It is also important support for the sustainable development of economy and society. According to the latest energy development report, the growth rate of energy consumption in China has continued to rebound, while the structure of energy consumption has been significantly optimized. In terms of energy supply, the energy production in China has rebounded rapidly in 2018, with a total production volume of 3.77 billion tons of standard coal and a year-on-year increase of 5%, which is the highest record in 7 years. The overall situation of energy supply and demand is still loose in China. However, there are still tight supply situations in individual regions and individual time periods.

In 2018, after meeting the scaling demand, the energy industry in China has taken an important step toward high-quality development. In particular, the energy efficiency of Chinese energy industry is at the advanced level all over the world, which is continuously improving. The utilization rate of coal and the refining capacity are significantly improved. However, the external dependence of energy is increased further. The security situation has deteriorated. The external dependence on crude oil of Chine has climbed to 71%. The natural gas import has surpassed Japan to become the largest worldwide, with the external dependence reaching 43%. The dependence on foreign energy in China has continued to rise. The report predicts that the total electricity consumption of the whole society will increase by about
5.8% in 2019. The coal demand is 3.95 billion tons, and the power industry is still the main industry affecting coal consumption. The oil consumption is about 620 million tons, which has increased 1.6% year-on-year. The growth rate of natural gas consumption has slowed down. The annual consumption is about 310 billion cubic meters, which has increased 10.4% year-on-year. As a safer gas, natural gas not only improves the environmental pollution throughout the utilization but also is economical. It is an energy source that is beneficial to production and life.

With the advent of the Internet era, the demand for electricity is growing since many electronic products have become a necessity for people. At the same time, because of the conversion of other energy sources into electric energy, a lot of energy is lost, and the environment is polluted to some extent. Therefore, the planning of integrated energy has become an important task for relevant experts. At present, the coupling problem of natural gas, which is a clean gas, and electric energy is getting more attention from relevant experts.

Therefore, the construction of an integrated energy planning mathematical (EPM) model for coupling natural gas and electricity is very important for studying the coupling problem of electricity and gas, as well as the planning and utilization of integrated energy. It is also believed to be important in the rational utilization of energy and efficient operation.

2. Literature review

With the continuous changes in the global environment, the use of energy has become a hot topic of concern. Especially, the research of integrated energy systems has become a key task in the energy field.

Based on the analysis of electric power and natural gas system (NGS), Wang Weiliang et al. (2017) built a solution model for the steady-state analysis of the electric-gas coupled integrated energy system with the energy hub as the core. Also, they explored the characteristics of the NGS network and its impact on regional integrated energy systems. The results showed that the integrated model could effectively reflect the impact of state changes in NGS network on other coupled systems [1]. Wei Zhinong et al. (2017) simulated the multi-period transient energy flow of the electricity-gas interconnected integrated energy system. In the short time scale study, the steady-state model of the natural gas system and the calculation results of the transient model were significantly different [2]. Yang Zijuan et al. (2017) analyzed the related researches on the coupling system of electric power and natural gas network. Also, they expounded the universality and commonality of NGS modeling and introduced the collaborative optimization research on the power system and natural gas system, which was a preliminary outlook of the dual network coupled system [3].

In summary, the previous documents have focused on the study of energy coupling systems. However, the construction of the mathematical model is insufficient. Therefore, the construction of energy-coupling integrated energy planning model is of practical significance for the rational utilization of energy resources and environmental protection.

3. The construction of an integrated EPM of dynamic natural gas-electricity coupling

The NGS has certain similarities with the power system. It is especially obvious in terms of steady-state modeling and power flow analysis characteristics. Therefore, it can be studied with reference to the existing analysis ideas of the power system. The main difference between NGS and power system is that the former has large-scale storage characteristics and special requirements for temperament. The analysis of such difference is often the key to improve the quality of the energy supply of integrated energy systems. Natural gas itself is composed of a variety of gas components. In addition, its temperament will change after the introduction of other types of natural gas or new gas injection points. Also, due to economic dispatch and demand-side management, the load regulation of NGS may cause its network status to change. For the above phenomena, traditional NGS analysis methods are often difficult to be applied. In this study, the influences of natural gas temperament changes, the load adjustment, and the gas injection point on the NGS and other parts of the regional integrated energy system with which it is coupled are mainly discussed. The way to construct an applicable natural gas system analysis model and integrated steady-state is the key to the solution framework [4].
The relevant data in 2018 pointed out that the energy consumption structure of China has undergone a certain change, as shown in Figure 1:

![Figure 1](image_url)

Figure 1. The energy consumption structure in 2017 and 2018

Figure 1(a) shows the data in 2017, and Figure 1(b) shows the data in 2018.

As shown in Figure 1, after the adjustment of energy consumption in China, the structure of energy consumption has achieved remarkable results. Clean and low-carbon energy has become the driving force for structural adjustment. Natural gas consumption continues to grow, and its consumption growth has set a world record, as shown in Figure 2:

![Figure 2](image_url)

Figure 2. The consumption of natural gas from 2013 to 2018 in China

The proportion of natural gas consumption has increased on a yearly basis, which also indicates that the energy consumption structure in China is continuously optimized. The annual natural gas consumption in 2018 has exceeded expectations by reaching 280.8 billion cubic meters. Especially, the growth rates of city gas and power generation are rapid. As an important condition for production and living, electricity has also increased by 1.9 percentage points compared with 2017, creating a new record in 2018, as shown in Figure 3:
Figure 3. The monthly growth rate of power consumption from 2017 to 2018 in China

As shown in Figure 3, the rapid growth of the tertiary industry and residential electricity consumption is an important driving force for the sustained and rapid growth of electricity consumption in the whole society. Therefore, the growth rate of power consumption continues to increase, which also provides opportunities for coupling between energy sources.

The coupling of natural gas and electric energy is carried out to make full use of energy resource. Power systems usually require transformers and internal nodes, while NGS requires compressors, pressure, and flow nodes to ensure proper system operation [5].

When constructing the model of the electricity-gas coupling integrated energy system, two energy networks are involved, i.e., the power grid and the natural gas network. The power network model involves the active and reactive power balance equations. The natural gas network involves the hydraulic model and the fluid model. Modeling of the natural gas network involves pipeline pressure drop equations, nodal flow equations, and ring energy equations, which can be analogized to the Ohm’s law of the grid, Kirchhoff’s current law, and Kirchhoff’s voltage law. The natural gas network is mainly composed of a long-distance gas transmission network and a town gas pipeline network. The natural gas is mainly mined from the gas field or provided by an external gas source, which is then transported to the natural gas gate station near the city, as well as the industrial areas, through a long-distance gas pipeline. The gate station serves as the starting point for the urban gas network. After pressure regulation and processing, it is then powered by pipelines and pressure regulating stations near the user terminals.

From the perspective of coupling, the high-pressure gas network is connected to the gas-fired power plant, which has a high degree of correlation with the power grid [6].

The solution of the IES natural gas pipeline network trend focuses on two types of variables, i.e., the pipeline pressure and the node flow. Since natural gas is a compressible fluid, the different local conditions of the network determine the unstable flow of natural gas, resulting in changes in pipeline pressure and flow. The parameters that determine the flow of natural gas include pressure, density, and flow rate, all of which are functions of pipe distance and time.

In this process, the electric gas transfer device needs to be modeled. The Power to Gas (P2G) device is actually a device that uses electricity as an input to generate hydrogen by electrolyzing water, and then uses hydrogen to produce methane. With the promotion of natural gas and the development of hydrogen energy technology, the importance of P2G is becoming more dominant whether it is deployed...
in energy storage facilities or in a power-gas joint network. P2G achieves the conversion of electrical energy to natural gas energy flow compared to the way that gas turbines burn natural gas. Under normal circumstances, the conversion efficiency of the electrolytic cell can reach 70%-90%, and the overall conversion efficiency of P2G can reach about 50%. If the subsequent gas power generation is considered, the efficiency of P2G will be only 30-40%.

Since the demand for electricity and natural gas in production and life is a dynamic process, further analysis of its mixed energy flow is needed. In a power-natural gas interconnected network, a gas turbine consumes natural gas flow to output electrical energy, and a P2G device consumes electrical energy to output natural gas flow. If the equilibrium node of the natural gas network is the injection node of the natural gas source when the current flow of the gas network fluctuates, there will be a gas source for the balance of the natural gas pumping, and the coupling between the different energy flows is 0. When the power network is connected to the external power grid, the balance node is in the external network, and the external power grid node balances the power flow. At this time, the coupling between the different energy flows is still 0.

According to the different selection methods of the grid and gas network balance nodes, the electric-gas interconnection IES system has four modes of operation. The first type of operation mode is to select a gas turbine as the grid balance node for the grid, and the gas grid selects a P2G device as the gas network balance node. Only the new energy, such as wind power inside the region, is used as the source for power generation. It is a fully coupled operating state. The second type of operation mode is that the gas network selects the non-P2G gas source as the balance node, and the grid selects the gas turbine as the balance node. Then, the two networks are in incompletely coupled operation states. The third type of operation mode is to select P2G as the balance node for the gas network, and the non-gas turbine as the balance node for the grid, in which the two networks are also incompletely coupled. The fourth type of operation mode is that the grid and the gas network simultaneously select non-gas turbines and non-P2G gas sources as balance nodes and the system realizes complete decoupling operation.

In the optimization process, the integrated energy planning model needs to aim at the minimum cost, including the total operating cost of the power network and the natural gas network within 24 hours. The total operating cost of the power network and the price parameters are related to the hourly output of each coal-fired unit.

The total operating cost of a natural gas network is related to the cost of each gas source in the natural gas network, as well as the flow per hour of each gas source. In the coupling process, the coupling element device has certain constraints in both the gas turbine and the electric gas converter. At the same time, the two networks are mutually coupled through the gas turbine and the P2G device. Also, the power network has wind power access. The natural gas network of the electric-gas interconnection network has an external air source, and the power network part has an external coal power generation access. Among them, 4 coal-fired units and 6 gas turbines are connected to the grid. Meanwhile, 3 wind farms are connected to the grid. In the natural gas network, 3 P2G devices and 4 external air sources are connected.

During the solving process, when the gas load of the natural gas network is low, it is just like the time when the electric load of the power network is low. At this time, the super-generated wind power generates methane through the electric gas transfer device, thereby supplying gas to the natural gas load. When the gas load is at the peak period, the electric load is also at the peak period. At this time, the gas turbine needs to be put into operation to meet the electric power balance, and the flow rate of the purchased gas source also reaches a peak at this time. At this point, the total cost of the system can reach $750,335 USD, while the cost of the grid and the natural gas network is $587,220 USD and $163,305 USD, respectively.

It can be seen that the coupling of natural gas and electricity can comprehensively use energy for production and living, which saves energy to a certain extent. Also, the total system cost is also lower than the cost of mono-network, indicating that the model can reduce the operating costs and helps in the integrated utilization of energy.
4. Conclusion

The mathematical planning method is used to construct an integrated EPM model for natural gas-electric energy coupling, which can improve the efficiency of energy utilization, ensure the safe and stable operation of the grid and natural gas network, and realize the integrated utilization of energy resource. However, in this study, only integrated energy planning is modeled. The conversion between the two energy sources is not considered, which will be studied in subsequent research. The construction of the integrated EPM of dynamic natural gas-electricity coupling will not only further explore the important issues in the coupling process between natural gas and electricity but also provide particular suggestions for the development of these two energy systems, thereby providing reference for the energy planning of other resources.

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