The Optimal Operation Model of Electric-Thermal-Gas Integrated Energy System Considering Multi-Energy Complementarity

Ailin Zhao¹*, Jiaxin Ma¹, Xichao Zhou², Lin Cong², Baohua Bai², Ming Zeng¹, Xiaochun Zhang¹
¹ School of North China Electric Power University, Beijing, China
² State Grid Integrated Energy Service Group, China

*Corresponding author e-mail: 120192206949@ncepu.edu.cn

Abstract. As China's environment and climate problems become more and more serious, the integrated energy system is booming. However, the coupling between various systems is not strong, and it is urgent to increase the coupling between multiple systems. Taking the total cost of the integrated energy system as the objective function, the independent operation and coupling transformation of the power system, natural gas system and thermal system within the system are considered. In this paper, a system planning model is built to meet the three types of loads in the system: electric load, thermal load and gas load, so as to increase the coupling of the system, ensure the reliable operation of the integrated energy system and improve the energy utilization efficiency.

1. Introduction
In recent years, China's energy consumption structure with fossil energy as the main body has brought serious environment and climate problems, the pressure of energy conservation and emission reduction has also increased. Therefore, improving the energy utilization efficiency and the energy structure with clean energy as the main body has become the inevitable trend of sustainable economic development. As the premise of the construction of smart grid and energy Internet, the integrated energy system is booming. It can realize the complementary advantages of various energy sources and improve the utilization efficiency of energy, which has become a specific way to solve the energy problem. However, the coupling between the power system, thermal system, natural gas system and other systems are not strong. So it is urgent to increase the coupling between the multiple systems to improve the system's ability to resist risks and ensure the safe and reliable operation of the integrated energy system.

At present, the study of integrated energy system operation optimization, which is concentrated in a particular scenario to achieve low carbon and economic goals, in an integrated energy system cost minimum as the optimization results, with the power constraints of each system, output interval constraint, energy storage capacity constraints, and controllable unit climbing output as constraint conditions, the optimization model of the integrated energy system is constructed. In reference [1], wind curtailment cost, environmental pollution cost and ES-HS loss cost are considered in the construction of scheduling cost model of regional integrated energy system, so as to improve the problem of poor scheduling economy. In reference [2], the operating costs under four scenarios are compared, with the
balance of power supply, balance of heating (cooling) and operation of micro gas turbine as constraint conditions. In reference [3], under the condition of utility maximization of energy suppliers and users, a coalition game based optimum operating method for integrated energy system is proposed, and a bi-level optimization model of integrated energy system considering the comprehensive demand response of new energy generators is established. In reference [4], the energy flow model and security constraints of the power-to-gas power system and natural gas system are considered, and the carbon dioxide emissions are converted to the economic dimension and the system operating cost together to form the objective function with the lowest comprehensive cost, so as to construct the optimal operation model of the integrated energy system. In addition to considering the general constraints of the operation optimization of the integrated energy system, the reference [5] establish an optimal model of the integrated energy system including cross-chain transaction of the green certificate by considering the market price of green certificate, green certificate quota, electric bus balance, hot water bus balance and steam bus balance, etc. In reference [6], the optimization model of community-level integrated energy system is constructed, considering constraints such as power balance, output limit of generation equipment, capacity of energy storage device and charge and discharge of energy storage device, and an objective function including direct operation cost and comprehensive carbon cost is established.

For the operation of the integrated energy system optimization problem, considering the system internal power system, gas system, heating system run separately and coupled into three parts, the minimum total cost integrated energy system as the objective function, with the capacity and power balance as constraint conditions, constructed for the system electrical load, heat load, the gas load system planning model of three kinds of load.

2. Basic architecture of an integrated energy system

The integrated energy system is a complex coupling system composed of power system, natural gas system and heat (cold) system. In the process of energy construction and planning, the energy is organically coordinated and planned through the production, supply, conversion, storage and consumption of all kinds of energy. Its basic structure lies in the physical composition of the integrated energy system, that guarantee the basic operation of the integrated energy system. A scientific, comprehensive and accurate description of the basic architecture of the integrated energy system is the basis of multi-scale system modeling for the integrated energy system. This paper describes the basic architecture of the comprehensive energy system from three parts: energy supply side, transmission and distribution side and consumption side. The basic architecture is shown in Figure 2-1.

The energy supply side is the upstream market. The upstream market generally consists of the electricity market, the heat market and the natural gas market. On the one hand, the primary energy and secondary energy are transmitted to the demand side for users to use. On the other hand, wholesale to integrated energy system operators, through a variety of ways, primary and secondary energy can be efficiently and quickly converted into a variety of energy forms, so as to meet the energy needs of different users on the demand side.

The energy transmission and distribution side is the integrated energy system operator. The integrated energy system operator consists of a regional energy system control center and a variety of production, conversion and storage facilities. On the one hand, the regional energy control center receives the energy wholesale demand response information and energy trading demand response instructions from the upstream market and the demand side; on the other hand, it telemetry the production equipment, conversion equipment and storage equipment. Production equipment is small-scale renewable power generation system, which generally includes distributed photovoltaic power generation, combined heat and power (CHP) unit and combined cooling heating and power (CCHP) system. Conversion equipment to include gas turbine, gas boiler, hydrogen fuel cell and other equipment. Storage equipment is an auxiliary equipment including energy storage batteries, heat storage tanks and gas storage tanks.

The energy consumption side is the demand side. The demand side is generally composed of typical users of industrial parks, typical users of public institutions, typical commercial users and typical users.
The first way to obtain energy on the demand side is to purchase energy directly from the upstream market, and the second way is to obtain energy supply services from integrated energy system operators through energy transmission network, including power grid, heating network and cold network. In addition, the demand side provides transaction data for the regional energy control center to implement load monitoring.

Figure 1. Basic architecture of an integrated energy system.

3. Establishment of mathematical model for optimal operation of integrated energy system

The model mainly considers the gas turbine, energy storage and other equipment to meet the user's load demand of electricity, heat and gas, and takes the minimum cost of operation as the objective function to realize the economic operation of the system. Specifically, the electric load meets the user's electricity demand through the wind power generation system, photovoltaic power generation system and gas turbine, the thermal load meets the user's heat demand through the gas boiler, and the gas load meets the user's gas demand through the P2G.

3.1. System constraints

In this paper, the integrated energy system depends on wind power generation system, photovoltaic power generation system, gas turbine, P2G, boiler and energy storage system.

3.1.1. Wind power generation.

\[ P_{w, t}^\text{min} \leq P_{w, t} \leq P_{w, t}^\text{max} \]  

(1)
In the formula, $P_{wt}^{\text{max}}$ represents the rated power of wind power output at time $t$; $P_{wt}^{\text{min}}$ is a wind turbine.

### 3.1.2. Photovoltaic power generation system.

$$P_{pv,t} = AI \eta_{pv}$$

In the formula, $A$ is the photovoltaic installation capacity; $I$ is the intensity of sunlight; $\eta_{pv}$ is photoelectric conversion efficiency.

### 3.1.3. Gas turbine.

The gas turbine of the system is driven by the gas turbine through natural gas compression and mixed combustion with the fuel indoor fuel to generate electricity from rotation to realize the transformation of gas to electricity.

$$P_{DG,t}^{\text{min}} \leq P_{DG,t} \leq P_{DG,t}^{\text{max}}$$

$$P_{DG,dn,t}^{\text{min}} \leq P_{DG,t} - P_{DG,up,t} \leq P_{DG,up,t}^{\text{max}}$$

In the formula, $P_{DG,t}$ is the power of gas turbine; $P_{DG,t}^{\text{max}}$ is the upper limit of power of gas turbine; $P_{DG,t}^{\text{min}}$ is the lower limit of power of gas turbine; $P_{DG,dn,t}$ is the lower limit of power of gas turbine climbing; $P_{DG,up,t}^{\text{max}}$ is the upper limit of power of gas turbine climbing.

### 3.1.4. P2G.

$$P_{P2G,t} = P_{P2G}^{gas,t} \eta_{P2G}$$

In the formula, $P_{P2G,t}$ is the power of P2G electricity to gas generation, $P_{P2G}^{gas,t}$ is the electric power of P2G input, and $\eta_{P2G}$ is the efficiency of P2G equipment.

### 3.1.5. Boiler.

In this model, boilers are divided into electric boilers and gas-fired boilers. The electric boiler realizes the conversion of electricity to heat, while the gas-fired boiler realizes the conversion of gas to heat by burning natural gas.

1. **Electric boilers**

$$P_{EB,t} = P_{EB,t}^{ele,t} \eta_{eg}$$

In the formula, $P_{EB,t}$ is the thermal output power of the electric boiler; $P_{EB,t}^{ele,t}$ is the electric power of the electric boiler, and $\eta_{eg}$ is the electric-to-thermal efficiency of the electric boiler.

2. **Gas-fired boilers**

$$P_{GB,t} = P_{GB,t}^{gas,t} \eta_{gg}$$

In the formula, $P_{GB,t}$ is the power of gas boiler thermal output, $P_{GB,t}^{gas,t}$ is the gas to heat efficiency of gas boiler, and $\eta_{gg}$ is the gas power of gas boiler.

### 3.1.6. Energy storage system.

1. **Gas storage device**

$$P_{GS,t} = P_{GS,t-1} + P_{in,t} \eta_{gs} - P_{dl,t} \frac{P_{gas}^{gas}}{\eta_{gpl}}$$
\( P_{GS,t} \) is the gas storage power of the gas storage tank at time \( t \), \( P_{\text{gas},t} \) is the gas storage power of the gas storage tank, \( \eta_{pr} \) is the gas retention efficiency, \( P_{rl,t} \) is the gas release power of the gas storage tank, and \( \eta_{rl} \) is the gas release efficiency.

(2) Thermal storage device
\[
P_{HS,t} = P_{HS,t-1} + P_{he,t} \eta_{he} - \frac{P_{he,t} \eta_{he}}{\eta_{he}}
\]

\( P_{HS,t} \) is the gas retention power of the heat storage tank at time \( t \); \( P_{he,t} \) is the heat storage power of the heat storage tank; \( \eta_{he} \) is the thermal retention efficiency; \( P_{rl,t} \) is the power released by the gas storage tank; \( \eta_{rl} \) is the gas release efficiency.

3.2. Power balance constraint
In addition to meeting the power constraints of each system above, the power power of the whole region needs to be maintained in a balanced state:

3.2.1. Electric power balance.
\[
P_{pv,t} + P_{w,t} + P_{DG,t} = P_{P2G,t} + P_{ES,t} + P_{aE,t}
\]

In the formula, \( P_{aE,t} \) is the user's power load.

3.2.2. Thermal power balance.
\[
P_{EB,t} + P_{GB,t} = P_{aH,t} + P_{HS,t}
\]

In the formula, \( P_{aH,t} \) is the user's power load.

3.2.3. Gas power balance.
\[
P_{P2G,t} = P_{aG,t} + P_{GS,t}
\]

In the formula, \( P_{aG,t} \) is the user's power load.

3.3. Objective function
The objective function of the model is to minimize the optimized operation cost of the comprehensive energy system:
\[
\min Q = k_w P_{wt} + k_p P_{pv} + k_{DG} P_{DG} + k_{P2G} P_{P2G} + k_{EB} P_{EB} + k_{GB} P_{GB}
+ k_{ES} P_{ES} + k_{HS} P_{HS} + k_{GS} P_{GS} + C_{ele} + C_{gas} + C_{he}
\]

In the formula, \( k_w \) is the unit cost of wind power unit; \( k_{pv} \) is the unit cost of photovoltaic units; \( k_{DG} \) is the unit cost of gas turbine; \( k_{P2G} \) is the unit cost of P2G equipment; \( k_{EB} \) is the unit cost of electric boiler; \( k_{GB} \) is the unit cost of gas-fired boiler; \( k_{HS} \) is the unit cost of the heat storage tank; \( k_{ES} \) is the unit cost of the battery; \( k_{GS} \) is the unit cost of the gas storage tank; \( C_{ele} \) is the cost of electricity; \( C_{gas} \) is the cost of gas; \( C_{he} \) is the cost of heat.

4. Conclusion
This paper studies the optimal operation of the integrated energy system. Firstly, the basic architecture of the integrated energy system is introduced, which lays the foundation for the multi-scale system
modeling of the integrated energy system. Then, the optimization model of the integrated energy system is constructed. The objective function of the model is to minimize the optimized operation cost of the integrated energy system, and it mainly considers the gas turbine, energy storage equipment and so on to meet the load demands of users, such as electricity, heat and gas, so as to realize the economic operation of the system.

Acknowledgments
This work was financially supported by State Grid Corporation Technology Project (Research and application of integrated energy system regulation technology of power source, grid, load and storage interaction (No. SGFJJY00GHJS1900066)).

References
[1] Liu Hong, Chen Xingqi, Li JiFeng, Xu Ke. Economic scheduling of regional electric and thermal integrated energy system based on improved CPSO algorithm[J], Power Automation Equipment, 2017,37(06):193-200.
[2] Pan hua, Liang Zuofang, Xiao Yuhan, Qi Haonan, Xue Shujiao, Xue Qiangzhong. Optimized operation of regional integrated energy system under multiple scenarios[J], Journal of Solar Energy, 2021,42(01):484-492.
[3] Cong Hao, Wang Xu, Jiang Chuanwen, Yang Meng. Optimal operation method of integrated energy system based on game theory[J], Power System Automation, 2018,42(14):14-22.
[4] Gong Xiaqin, Wang Jin, Wang Long, Zhang Han, Qian Jiahui, Deng Minghui. Low-carbon economic operation of electricity-gas interconnection integrated energy system containing electricity to gas[J], Journal of Electric Power Science and Technology, 2020, 35(02):76-83.
[5] Luo Zhao, Qin Jinghui, Liang Junyu, Zhao Ming, Wang Hao, Liu Kezhen. Optimized operation of integrated energy system with green certificate cross-chain transaction[J/OL], The Grid Technology:1-10 [2021-03-03]. https://kns-cnki.net.cn/kcms/detail/11.2410.TM.20210203.1542.007.html.
[6] Chen Hua, Huang Haiye. A community-level integrated energy system optimization model considering carbon emissions[J], Journal of Shanghai electric University, 2020,36(06):613-618.
[7] Zhang Min, Wang Jinhao, Chang Xiao, Yang Chaoying, Li Ran, Sun Changwen, Fan Rui. Multiobjective robust planning method for thermal-electrical-coupled micro-energy systems considering renewable energy uncertainties[J/OL], China Power:1-11 [2021-03-09]. https://kns-cnki.net.cn/kcms/detail/11.3265.TM.20210308.1411.002.html.
[8] Pu Yuan, Cheng Haizhong, Song Yi, Yuan Kai. Calculation of optimal energy flow in a regional integrated energy system taking into account multi-energy coupling[J/OL], Electrical Measurement and Instrumentation:1-8 [2021-03-09]. https://kns-cnki.net.cn/kcms/detail/23.1202.TH.20210307.1152.002.html.
[9] Li Peng, Wang Zixuan, Wang Nan, Yang Weihong, Li Mingzhe, Guo Tianyu, Yin Yunxinn, Wang Jiahao, Guo Tianyu. Stochastic robust optimal operation of community integrated energy system based on integrated demand response [J], International Journal of Electrical Power and Energy Systems, 2021,128.
[10] Lv Zhenhua, Li Qiang, Han Huachun. Modeling and simulation of power-gas interconnection in an integrated energy system [J], Report of Science and Technology, 2021, 37(02): 75-80+85.
[11] WeiWei. Key technologies of integrated energy system planning, analysis and control [J], Power Engineering Technology, 2021,40(01):1.
[12] Bai Hongkun, Zhang Peng, Yin Shuo, Yang Meng, Yang Qinchen. Operational optimization of multi-storage regional integrated energy system considering integrated demand side responses [J], Journal of Henan University of Technology (Natural Science Edition). 2021,40(02):127-134.