Multi-objective Day-ahead Optimal Scheduling for Integrated Energy Systems

2024 6th Asia Energy and Electrical Engineering Symposium (AEEES) | 979-8-3503-7347-9/24/$31.00 ©2024 IEEE | DOI: 10.1109/AEEES61147.2024.10544737

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***Abstract*—Against the background of the current increasingly tense global energy situation, improving energy utilization efficiency, reducing energy consumption and reducing environmental pollution have become urgent issues for governments and enterprises. The utilization of combined heat and power (CCHP) units is a key way to improve the consumption of renewable energy. However, the carbon emission of CCHP poses a challenge to the pollution and economic optimization of integrated energy systems. To address this challenge, this paper proposes a novel optimal scheduling model for cogeneration with power-to-gas (P2G) and carbon capture system (CCS) considering the choice of cogeneration mode, which solves the carbon source problem required for P2G and the carbon emission problem of cogeneration through IES optimal scheduling. The model takes CCHP, P2G and CCS as a whole system, establishes the operation law of the model, and analyzes the coupling characteristics of electricity, heat, gas and carbon of the model. Accordingly, the optimization strategy of IES considers the proposed model and carbon trading mechanism, and then solves and verifies the validity. The research and application of the model can help improve the operational efficiency of the energy system, reduce energy consumption and environmental pollution, and provide strong support for building a sustainable energy system.**

***Keywords*—CCHP, P2G, CCS, day-ahead**

I. INTRODUCTION

In the face of the energy crisis and the problem of climate warming, renewable energy sources are becoming more and more important in human life as traditional fossil energy sources are being depleted. Moreover, renewable energy is mostly clean energy, and renewable energy is widely adopted to reduce environmental pollution. However, the new energy output itself is characterized by uncertainty, intrmittency and volatility, and it is a challenging problem to consume new energy from the perspective of scheduling. In the current context, with global climate change and environmental pollution becoming more and more serious, governments and enterprises are actively promoting energy transformation and developing renewable energy and clean energy. The National Energy Administration (NEA) has released the "14th Five-Year Plan for Modern Energy System", which puts forward the goal of accelerating the construction of a modern energy system. The plan emphasizes the need to vigorously develop the new energy industry, promote the revolution of energy production and consumption, and promote the synergistic development of energy and economy and society. With the development of new energy on an increasingly large scale, the phenomenon of abandoned wind and light has gradually become prominent, causing widespread concern, and how to increase the utilization rate of new energy has become a hot issue nowadays.

Comprehensive energy system can promote the gradient utilization of energy as well as the coordination and complementarity of multiple energy sources, which is of great significance in promoting the consumption of clean energy and reducing carbon emissions[1]. As a system that integrates multiple energy resources, the core idea of integrated energy system is to integrate various energy resources to form a unified energy supply network. The development of integrated energy system provides new possibilities for realizing efficient energy utilization and ecological environment improvement [1] Through intelligent control and optimal scheduling, the system can flexibly adjust the proportion and distribution of various energy sources according to the actual demand and market conditions for achieving the best energy consumption effect. As an important part of the integrated energy system, the utilization of combined heat and power (CCHP) units is a key way to improve the consumption of renewable energy. However, renewable energy consumption has become more

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challenging due to the increased demand for heat loads from combined heat and power (CCHP) units. At the same time, the extensive use of fossil fuels leads to the release of large quantities of carbon dioxide (CO2), resulting in the greenhouse effect. Therefore, optimization of integrated energy systems (IES) can improve the efficiency of renewable energy use and the operational flexibility of the system.

Thermal storage is often used to decouple the electrical-thermal characteristics of CHP units to improve wind power adaptation. Using a combination of thermal storage as in [3], energy storage and electric heaters to improve the flexibility of cogeneration units and to facilitate wind power conditioning, but there is a delay in the heat grid response to cogeneration. It proposes an optimal scheduling method for an integrated electricity-heat energy system considering the dynamic characteristics of the heat network and carbon trading as in [4]. On the basis of considering the dynamic characteristics of the heat network, an optimal scheduling model of the electricity-heat integrated energy system is constructed by energy coupling equipment such as cogeneration units, heat pumps and gas turbines. It addresses the problem of large-scale wind energy consumption and low-carbon optimal scheduling of urban integrated energy system (UIES), and proposes a low-carbon optimal scheduling method of UIES considering electricity-hydrogen-HCNG coupling and demand response under the framework of source-network-charge-hydrogen cooperative optimization as in [5]. To reduce the operation cost and carbon emission of the integrated energy system in the park, and at the same time to cope with the stochastic fluctuation caused by system uncertainty, a low-carbon economic dispatch model of the integrated energy system in the park considering stepped carbon trading is proposed and solved by deep reinforcement learning method as in [6].

To enhance the flexibility of cogeneration instead of heat storage as in [7]. P2G serves as a connecting link between the power system and the natural gas system to convert electrical energy into natural gas[1]. Traditional P2G systems only consider methane as the fuel for gas-fired units and do not fully utilize the high electrolysis rate of hydrogen, resulting in an increase in the number of energy ladder conversions and higher energy losses. It applies the hydrogen and methane coupled gas grid hydrogen injection technology produced in two stages of P2G system to promote the consumption of renewable energy in IES as in [9]. Based on the concept of energy hub, the optimal scheduling of IES system economics is transformed into a mixed integer programming problem for solution. To promote the cleaner transformation of IES and explore a reasonable transaction model between operators and users, a two-tier optimal operation strategy of IES containing a photovoltaic power plant and CCS-P2G coupling is proposed [1]. Based on carbon capture and power-to-gas (P2G) technology as in [11], it builds a framework of zero-carbon power-to-gas integrated energy system, collects carbon dioxide generated by coal-fired units by installing additional carbon capture devices on coal-fired units, and converts carbon dioxide to methane as raw material through P2G technology, and also conducts in-depth research on the mathematical relationship between the thermal power unit output and the amount of methane generated, and establishes a day-ahead scheduling model with the goal of minimizing the comprehensive operating cost. The day-ahead scheduling model is established with the goal of minimizing the comprehensive operating cost, and the zero-carbon goal of the integrated electricity-gas energy system is also considered. It proposes to categorize the loads participating in demand response on the customer side into rigid loads, price-sensitive loads and carbon price-sensitive loads, and to install additional P2G equipment in community operators as in [12]. Based on this, a dual-principle stepwise carbon trading mechanism involving users and IES operators is established, and a two-layer optimization model is built. To improve the flexibility and economy of power plants in a multi-energy system with high penetration of renewable energy, it considered the interactions between multiple energy carriers, such as cogeneration and P2G, to achieve the optimal scheduling of the interconnected system of electricity, gas, and heat as in [13]. However, in this study, the energy conversion of P2G requires the purchase of CO2, which imposes a carbon source cost CO2 on P2G.

Carbon capture system (CCS) technology is widely used in coal-fired or gas-fired power plants. CCS can capture CO2 emitted from cogeneration units through electricity. It is equivalent to increasing the electrical load of the CHP unit, improving the renewable energy consumption, and reducing the carbon emissions of the CHP unit. The combination of CCS and micro gas turbine is used to reduce the CO2 emissions of micro gas turbine[14]. Micro gas turbine flue gas has less CO2 and carbon capture efficiency than CHP units. CCS and P2G have also been developed for low carbon economic dispatch of electricity and gas networks. However, in this dispatch model, CCS stores the captured CO2 and transmits it over long distances to P2G, which requires transmission and storage costs.

Based on the above analysis, it is considered that the use of CCS to capture CO2 from CCHP to P2G to avoid long-distance transmission and storage can provide a CO2 source to P2G and reduce CO2 emissions from CCHP. Since its feasible range is jointly determined by P2G and CCS, the cogeneration output is reduced. Therefore, we developed CCHP, P2G, and CCS as an integrated system. In this way, the operating, transmission and storage costs are reduced and the environmental benefits of CHP with P2G and CCS are improved. However, the combination model and constraints of CHP with P2G and CCS, as well as the detailed analysis of energy and carbon flows, are not currently studied [1].

For IES optimization, flexibility is a key factor that contributes to wind power regulation. It studied IES dispatch models for CHP to improve its wind power regulation as in [16]. The flexibility of IES was investigated and the energy flow in the electricity, heat and gas network was optimized by cogeneration with thermal storage as in [17]. However, the flexibility of IES is not sufficient with CHP with thermal storage only. In CHP with P2G and CCS models, P2G can convert the electricity from CHP to gas, which contributes to the flexibility. Moreover, P2G is applied to optimize IES, but its carbon source needs to be purchased as in [18]. The contribution of P2G to low carbon is not utilized. It exploits the impact of P2G on low carbon in thermal power plants as in

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[19], while full carbon recovery is missing in IES optimization. Carbon trading is favored as part of the carbon allowances can be sold on the carbon trading market to increase revenues[1], thus reducing the operating costs of IES[1]. However, carbon trading has not yet been developed in the field of P2G and CCS.

Therefore, this paper proposes an IES optimal dispatch model for cogeneration and carbon trading based on the selection of FTL and FEL modes for cogeneration with P2G and CCS modes to facilitate the adaptation of renewable energy sources and the reduction of CO2 emissions. In P2G + CCS mode cogeneration, the feasible ranges of electricity, heat and gas power are determined based on their coupling characteristics. Relationships between electric power, thermal power and CO2 emissions were established for the cogeneration of P2G units and CCS units.

The contributions to the work of this patent are as follows.

1) Firstly, a new type of CHP with P2G and CCS modes considering the choice of CHP modes is proposed, and the operational characteristics of CHP with P2G and CCS modes are investigated.

2) An optimal dispatch model for IES based on carbon trading and cogeneration (P2G + CCS) was developed. The cogeneration with P2G and CCS affects the CO2 emission and renewable energy accommodation, and reduces the operation cost through carbon trading.

3) Compared to other conventional models, this method increases the amount of electricity generated from wind and PV, reduces CO2 emissions, and lowers the operating costs of the IES.

The rest of the paper is organized as follows. Section II describes the model and investigates the coupling of electric, thermal and gas power in CHP using P2G and CCS models, and establishes the IES optimal dispatch model, including the objective function, power balance and constraints of each unit.

In Section III, a numerical study is used to assess the validity of the proposed methodology with the actual data. Section IV draws conclusions.

II. Description and Modeling of Integrated Energy Systems

The integrated energy system studied in this paper is shown in Fig. 1. It mainly includes energy storage as well as microturbines, combined cooling, heating and power systems, photovoltaics, wind turbines, electricity-to-gas and other energy conversion devices. Among them, the models of the main components are constructed as follows.

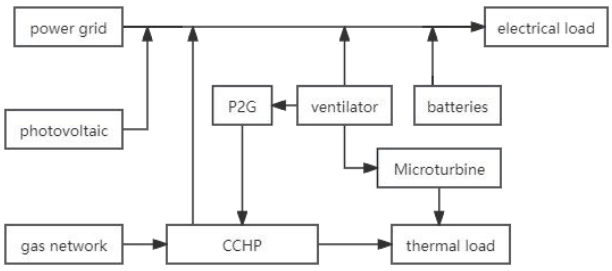


Fig. 1. Integrated energy system

A. Thermal Storage Tank (TST)

Heat storage tanks can increase the flexibility and economy of system operation by storing heat energy when there is excess heat and releasing it when there is insufficient heat or when heat production is costly. TSTs are required to satisfy the following power constraints and energy constraints.

$$\begin{cases} U_{tst,chr}^{t} H_{tst,chr}^{\min} \le H_{tst,chr}^{t} \le U_{tst,chr}^{t} H_{tst,chr}^{\max} \\ U_{tst,dis}^{t} H_{tst,dis}^{\min} \le H_{tst,dis}^{t} \le U_{tst,dis}^{t} H_{tst,dis}^{\max} \\ 0 \le U_{tst,chr}^{t} + U_{tst,dis}^{t} \le 1 \\ W_{tst}^{t} = W_{tst}^{t-1}\left(1-\gamma_{h}\right) + \int_{t-1}^{t} \left(\eta_{tst,chr} H_{tst,chr}^{t} - \dfrac{H_{tst,dis}^{t}}{\eta_{tst,dis}} \right) dt \\ W_{tst}^{\min} \le W_{tst}^{t} \le W_{tst}^{\max} \end{cases} \tag{1}$$

where $H_{tst,chr}^{t}$ and $H_{tst,dis}^{t}$ denote the thermal power stored/released by the TST at time t; $U_{tst,chr}^{t}$ and $U_{tst,dis}^{t}$ are binary variables denoting the charging/discharging state of the TST at interval t; $W_{tst}^{\min}$ and $W_{tst}^{\max}$ are the upper and lower limits of the thermal power released by the TST; γ_{h} is the energy loss rate of the TST; $\eta_{tst,chr}$ and $\eta_{tst,dis}$ denote the charging/discharging efficiency of the TST.

B. Cogeneration Modeling

Cogeneration, also known as combined heat and power production, is a highly efficient way of utilizing energy. It combines co-generation of electricity and heat to improve energy utilization efficiency by sharing energy waste heat. A cogeneration system generally consists of combustion equipment (e.g., gas turbines, steam boilers, etc.) and power generation equipment (e.g., generators). In such systems, the thermal energy generated by the combustion equipment is utilized to produce steam or hot water for heating, industrial production, or other purposes. At the same time, the thermal energy in the combustion equipment is utilized to drive the power generation equipment to produce electricity. In this way, heat and electricity can be utilized simultaneously.

The advantages of cogeneration lie in its high efficiency, low energy consumption and environmentally friendly features. It can significantly increase the efficiency of fuel utilization. Cogeneration systems are able to achieve higher total energy efficiency than separate power and heating plants. By recovering and utilizing waste heat, a CHP system reduces the need for fuel and reduces energy waste. Further, it reduces the impact on the environment. As a result of the efficient use of energy, carbon dioxide emissions are significantly reduced, reducing greenhouse gas emissions.

The power generation of a cogeneration system is a linear function of the recovered thermal energy. Typically, cogeneration is operated in a number of ways including fixing

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heat with electricity (FEL) and fixing electricity with heat (FTL).

(1) Electricity as a means of determining heat

The electricity to heat approach involves operating the microturbine to meet the electrical load. At the same time, the waste heat recovered from the heat recovery device is utilized to satisfy the thermal load . However, in some cases, the recovered heat cannot fully satisfy the heat demand. In such cases, electric boilers and heat storage tanks are required to supplement the insufficient heat load demand.

Microturbine generation must meet the needs of the electrical load.

$$\int_{t-1}^{t} E_{mt-FEL}dt = \int_{t-1}^{t} E_{req}dt \tag{2}$$

where E_{mt} is the power generated by the microturbine and E_{req} is the demand of the electrical load.

From equation (1), the fuel consumption of MT in interval t is given by.

$$\int_{t-1}^{t} E_{mt-FEL}dt = \int_{t-1}^{t} \frac{E_{mt-FEL}}{\eta_{mt}}dt \tag{3}$$

where F_{mt} is the fuel energy consumed by the MT and η_{mt} is the efficiency of the MT.

The heat energy produced by the waste heat recovery unit during the time interval t is as follows.

$$\begin{aligned}\int_{t-1}^{t} Qlrec-FELdt &= \int_{t-1}^{t}\left(F_{mt-FEL}-E_{mt-FEL}\right)\eta_{rec}dt \\ &= \int_{t-1}^{t} F_{mt-FEL}\left(1-\eta_{mt}\right)\eta_{rec}dt\end{aligned} \tag{4}$$

where Q_{rec} is the recovered waste heat energy and η_{rec} is the efficiency of the heat recovery unit.

Depending on the adequacy of the heat generated by the waste heat recovery unit to meet the heat load demand, the heat required by the gas boiler in zone t can be expressed as.

If $Q_{rec-FEL}^{t} \le Q_{ac}^{t} + Q_{he}^{t}$, where Q_{ac} is the heat energy required for an absorption chiller and Q_{he} is the heat energy required for a heat exchanger. Then $\int_{t-1}^{t} Q_{boil-FEL}dt = \int_{t-1}^{t} Q_{ac} + Q_{he} - Q_{rec-FEL}dt$, where Q_{boil} is the heat produced when the gas boils, otherwise $Q_{rec-FEL}^{t} > Q_{ac}^{t} + Q_{he}^{t}$.

$$\int_{t-1}^{t} Q_{boil-FEL}dt = 0 \tag{5}$$

The fuel consumed by gas boilers is as follows.

$$\int_{t-1}^{t} F_{boil-FEL}dt = \int_{t-1}^{t} \frac{Ql_{boil-FEL}}{\eta_{boil}}dt \tag{6}$$

where F_{boil} is the fuel consumed for gas boiling and η_{boil} is the efficiency of gas boiling.

According to equations (2) and (5), the total fuel consumption in FEL mode can be calculated as.

$$\begin{aligned}\int_{t-1}^{t} F_{FEL}dt &= \int_{t-1}^{t} F_{mt-FEL} + F_{boil-FEL}dt \\ &= \int_{t-1}^{t} \frac{E_{mt-FEL}}{\eta_{mt}} + \frac{Q_{boil-FEL}}{\eta_{boil}}dt\end{aligned} \tag{7}$$

(2) Heat to power approach

The heat-to-electricity approach means that the microturbines are allowed to operate with sufficient recovered waste heat to meet the heat and cooling requirements. Similarly, if the microturbine does not generate enough electricity to meet the requirements, the shortfall needs to be provided by the grid and the remainder can be stored in batteries.

The thermal energy provided by the waste heat recovery unit shall meet the thermal energy requirements of the absorption chiller and heat exchanger interval t.

$$\int_{t-1}^{t} Q_{rec-FTL}dt = \int_{t-1}^{t} Q_{ac} + Q_{he}dt \tag{8}$$

The fuel consumed by the microturbine during the time interval t is as follows.

$$\int_{t-1}^{t} Fl_{mt-FTL}dt = \int_{t-1}^{t} \frac{Q_{rec-FTL}}{\eta_{rec}\left(1-\eta_{mt}\right)}dt \tag{9}$$

The total electrical energy generated by the microturbine in the interval t is.

$$\int_{t-1}^{t} E_{mt-FTL}dt = \int_{t-1}^{t} F_{mt-FTL}\eta_{mt}dt \tag{10}$$

Microturbines may produce more or less power than the required electrical load. Assumption:

$$E_{mt-FTL}^{t} \le E_{req}^{t} \tag{11}$$

E_{grid} is the electricity provided by the grid. If $E_{mt-FTL}^{t} > E_{req}^{t}$, then $\int_{t-1}^{t} E_{\text{excess}}dt = \int_{t-1}^{t} E_{mt-FTL}dt - E_{req}dt$. E_{excess} is the excess electricity that should be stored. The total fuel consumed by the microturbine in the heat-and-electricity mode is.

$$\int_{t-1}^{t} F_{FTL}dt = \int_{t-1}^{t} F_{mt-FTL}dt \tag{12}$$

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C. Cogeneration Modeling with P2G and CCS

The coupled electric-thermal characteristics of cogeneration units pose a challenge for renewable energy regulation. In this section, a CCHP with P2G and CCS models is proposed to address this challenge. The cogeneration unit is equipped with P2G and CCS, and P2G includes two processes. First, the P2G produces hydrogen (H2) and oxygen (O2) in the process of water electrolysis by utilizing the electricity from the cogeneration. Second, H2 produced by CCS is utilized to generate CH4 with CO2 during CH4 synthesis, which enhances the power conditioning capability of the gas-producing CHP and reduces the thermo-electric coupling characteristics of the CHP unit. The CCS captures carbon dioxide and provides it to the P2G, which reduces the carbon dioxide emissions from the CHP. Thermal power is the portion of hot steam drawn from the CHP unit that is supplied to the heat load, and gas power is the power produced by burning one unit of natural gas.

In CHP with P2G and CCS modes, electrical energy is generated by the CHP $P_{e,t}$, which can be categorized into three parts according to their functions, as shown below:

$$P_e^t = P_{e1}^t + P_{e2}^t + P_{e3}^t \tag{13}$$

where P_{e1}^t is the power supplied to the grid, P_{e2}^t is the power consumed by the P2G, and P_{e3}^t is the power consumed by the CCS.

The gas from P2G can supply the gas load and the remaining gas is stored in the gas pipeline. Therefore, P2G has a lot of flexibility in renewable energy consumption. The relationship between P2G gas power and CCHP consumption power is given by the equation:

$$P_{gs}^{\mathrm{t}} = \alpha P_{e2}^t \tag{14}$$

where P_{gs}^{t} is the gas power generated by the P2G at moment t, and α is the electrical to gas power conversion efficiency of the P2G.

The amount of CO2 required for P2G was calculated from equation (3):

$$C_{cc}^t = \beta P_{e2}^t \tag{15}$$

where C_{cc}^t is the amount of CO2 needed for the electricity consumed , P_{e2}^t β (t/MWh) is the coefficient for calculating the amount of CO2.

In this paper, electrical energy is consumed in the process of capturing CO2.The CCS captures CO2 from the CCHP and transfers it to the P2G.The electrical power consumption of the CCS consists of the base power consumption (which can be regarded as a constant) and the operational power consumption. The operating power consumption is used to capture CO2, and the amount of capture is proportional to the amount of CO2 captured by the CCS. The electrical energy consumed by the CCS is given in the following equation:

$$P_{e3}^t = \chi C_{cc}^t \tag{16}$$

Cogeneration units have the constraint of "constant power with heat". According to the principle of operation, the electrical and thermal characteristics of a cogeneration unit can be described by equation (5):

$$\begin{aligned} &\max\{P_{e,\min} - C_{v1}P_h^t, C_m\left(P_h^t - P_{h0}\right)\} \\ &\le P_e^t \le P_{e,\max} - C_{v2}P_h^t \end{aligned} \tag{17}$$

In the formula, P_e^t is the electric power of the CHP unit at the moment t, $P_{e,\min}$ and $P_{e,\max}$ are the minimum and maximum electric power of the CHP unit, C_v is the electric heat conversion coefficient of the CHP unit, C_{v1} is the value of C_v corresponds to the minimum output power, C_{v2} corresponds to the maximum power output of the C_v value, C_m is the slope of linear power supply for CHP, P_{h0} is the power of the CHP unit with the minimum electric power, P_h^t is the thermal power of the CHP unit at the moment t.

III. Day Ahead Optimized Scheduling Model

In the day-ahead optimization phase, day-ahead renewable energy system and load forecasting and day-ahead mathematical modeling were performed at each time interval. The optimization plan was developed based on the operating modes of the integrated energy system equipment and power usage descriptions. The specific process is that for the kth interval, the optimized scheduling in the kth to k + Mth time intervals can be calculated by the day-ahead optimization model based on the forecast data solved in the rolling window period from the kth to k + Mth time intervals. Similarly, for the next step, the rolling window is moved to the next time interval and the optimized dispatch is recalculated based on the latest renewable energy system and load forecast data. In this paper, the time scale in the day-ahead rolling optimization phase is set to 1 hour. The rolling window length M is set to 4 h. For example, assuming k is equal to 1, the first time interval should be from the first hour to the fifth hour. The optimal scheduling for the first time interval is solved using the day-ahead optimization model. After that, the rolling window moves to the next time interval from the second hour to the sixth hour.

In the day-ahead optimization stage, some criteria should be developed as a basis for decision-making in determining the operation mode of the integrated energy system. Currently, most of the day-ahead optimization control strategies only consider the optimization of operating costs. However, as more and more impacts, such as carbon emissions, need to be taken into account due to concerns about environmental issues and

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climate change, single-objective optimization is no longer appropriate for energy supply systems. Operating costs, primary energy consumption , carbon dioxide emissions and load shedding costs are used as the basis for evaluating the operation of an integrated energy system. Using the above model, the optimization results of the integrated energy system in this paper can be further improved.

Therefore, PEC, CDE COST and LSC models are used to construct the optimization objective in IES operation. The objective function of IPC is obtained as follows.

A. Objective Function

1) Operating costs of CHP with P2G and CCS

$$\mathrm{COST}^{t}_{\mathrm{P2G-CCS}} = \sum_{t=1}^{T} [a(P^{t}_{e1} + P^{t}_{e2} + P^{t}_{e3} + C_{v1}P^{t}_{h}) + b(P^{t}_{e1} + P^{t}_{e2} + P^{t}_{e3} + C_{v1}P^{t}_{h})^2 + cP^{t}_{e2} + eP^{t}_{e3} + g] \quad (18)$$

where a, b, and g are the operating cost coefficients for P2G and CCS CHP, respectively; c and e are the O&M cost coefficients for P2G and CCS.

2) Carbon trading costs

In IES, day-ahead scheduling and CCHP equipped with P2G and CCS to reduce CO2 emissions, we use the baseline carbon emission control model. In this model, if the carbon emissions of IES are higher than the carbon intensity, it is necessary to purchase carbon credits in the carbon trading market.

Otherwise, carbon credits can be sold. The formula for calculating carbon emissions from IES is

$$\mathrm{CDE}^{t}_{\mathrm{FEL}} = F^{t}_{\mathrm{FEL}}\mu_f + \mu_c(P^{t}_{e2} + P^{t}_{e3} + C_{v1}P^{t}_{h}) + \mu_d(P^{t}_{e2} + P^{t}_{e3} + C_{v1}P^{t}_{h})^2 + C_{CO2} - C^{t}_{cc} \quad (19)$$

$$\mathrm{CDE}^{t}_{\mathrm{FTL}} = E^{t}_{\mathrm{gird}}\mu_e + F^{t}_{\mathrm{FTL}}\mu_f + \mu_c(P^{t}_{e2} + P^{t}_{e3} + C_{v1}P^{t}_{h}) + \mu_d(P^{t}_{e2} + P^{t}_{e3} + C_{v1}P^{t}_{h})^2 + C_{CO2} - C^{t}_{cc} \quad (20)$$

of which μ_f and μ_e are emission conversion factors for fuel and electricity, respectively; μ_c , μ_d , and C_{CO2} are emission factors for cogeneration. The integrated energy system should follow the smaller CO2 criterion for selecting the mode of operation.

The IES carbon allowances are

$$\mathrm{CEQ}^{t}_{\mathrm{IES-FEL}} = A\left(P^{t}_{\mathrm{FEL}} + P^{t}_{e2} + P^{t}_{e3} + P^{t}_{mt} + P^{t}_{wt} + P^{t}_{pv}\right) \quad (21)$$

$$\mathrm{CEQ}^{t}_{\mathrm{IES-FTL}} = A\left(P^{t}_{\mathrm{gird}} + P^{t}_{\mathrm{FTL}} + P^{t}_{e2} + P^{t}_{e3} + P^{t}_{mt} + P^{t}_{wt} + P^{t}_{pv}\right) \quad (22)$$

In the formula $\mathrm{CEQ}^{t}_{\mathrm{IES}}$ is the IES carbon emission quota at time t, and A is the unit electricity carbon emission quota. In this paper, we take the weighted average of the regional power marginal emission factor and the capacity marginal factor as 0.798, and P^{t}_{wt} is the wind power at time t, and P^{t}_{pv} is the photovoltaic power at time t.

As a result, the cost of carbon trading is reduced by

$$\mathrm{COST}^{t}_{\mathrm{CT-FEL}} = \sum_{t=1}^{T} \lambda(\mathrm{CDE}^{t}_{\mathrm{FEL}} - \mathrm{CEQ}^{t}_{\mathrm{IES-FEL}}) \quad (23)$$

$$\mathrm{COST}^{t}_{\mathrm{CT-FTL}} = \sum_{t=1}^{T} \lambda(\mathrm{CDE}^{t}_{\mathrm{FTL}} - \mathrm{CEQ}^{t}_{\mathrm{IES-FTL}}) \quad (24)$$

whereλ is the carbon trading cost factor

3) Fuel and electricity costs

$$\mathrm{COST}^{t}_{\mathrm{FEL}} = F^{t}_{\mathrm{FEL}}C_f \quad (25)$$

$$\mathrm{COST}^{t}_{\mathrm{FTL}} = E^{t}_{\mathrm{gird}}C_e + F^{t}_{\mathrm{FTL}}C_f \quad (26)$$

whereC_f is the unit price of natural gas, andC_e is the unit price of electricity purchased from the grid.

4) Penalty fees for abandoned wind and light

$$\mathrm{COST}_{\mathrm{wt-pv}} = \sum_{t=1}^{T} C_{wt}R^{t}_{cwt} + C_{pv}R^{t}_{cpv} \quad (27)$$

C_{wt} , C_{pv} are the unit prices of wind and light penalties, respectively; R^{t}_{cwt} , and R^{t}_{cpv} is the amount of wind and light abandonment in time period t.

5) Load shedding costs

If there is an interruption in supply and the load demand cannot be met, the load needs to be unloaded. The cost of load shedding is reflected as the economic cost to the society after load shedding. The direct economic loss caused by load shedding can be calculated by multiplying the economic loss per unit by the capacity to cut off the load. The formula for calculating the cost of load shedding is as follows.

$$\mathrm{LSC}^{t}_{\mathrm{IES}} = \sum_{i} C^{t}_{i}p^{t}_{i} \quad (28)$$

where $\mathrm{LSC}^{t}_{\mathrm{IES}}$ denotes the load shedding cost at moment t, i denotes each cutoff load, and C^{t}_{i} denotes the value of unit energy of each cutoff load at moment t, and p^{t}_{i} denotes the capacity of each cutoff load at moment t.

An integrated energy system will seek an optimal solution between load shedding and meeting the demand for electricity. The objective function is to minimize the cost of natural gas, the cost of grid supply and the cost of load shedding. As shown in the following equation, the energy demand supply rate can be controlled by setting an appropriate load shedding cost.

$$\min(C) = \mathrm{COST}^{t}_{\mathrm{P2G-CCS}} + \mathrm{COST}^{t}_{\mathrm{CT}} + E^{t}_{\mathrm{gird}}C_e + F^{t}C_f + \mathrm{COST}_{\mathrm{wt-pv}} + \mathrm{LSC}^{t}_{\mathrm{IES}} \quad (29)$$

B. Constraints

1) Power Balance Constraints

$$P^{t}_{mt} + P^{t}_{\mathrm{gird}} + P^{t}_{\mathrm{bt.dis}} - P^{t}_{\mathrm{bt.chr}} — P^{t}_{\mathrm{excess}} = P^{t}_{\mathrm{load}} - P^{t}_{pv} - P^{t}_{wt} \quad (30)$$

$P^{t}_{\mathrm{bt.chr}}, P^{t}_{\mathrm{bt.dis}}$ denote the charging and discharging power of the battery at time t

2) Heating Equilibrium Constraints

$$H^{t}_{mt}\eta_{\mathrm{rec}} - H^{t}_{\mathrm{boil}} — H^{t}_{ac} - H^{t}_{\mathrm{tst.dis}} + H^{t}_{\mathrm{tst.chr}} = H^{t}_{\mathrm{load}}/\eta_{\mathrm{he}} \quad (31)$$

$H^{t}_{\mathrm{tst.dis}}$ and$H^{t}_{\mathrm{tst.chr}}$, denote the thermal power stored/released by tst at time t

3) Cooling balance constraints

$$H^{t}_{ac}\mathrm{COP}_{ac} = Q^{t}_{c} \quad (32)$$

$\mathrm{COP}_{ac}$is the chiller performance factor,Q^{t}_{c} is the heat energy produced by the electric chiller

4) Gas power imbalance

The total gas power and gas load can be limited to

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$$P_{gl}^{t} + P_{mts}^{t} \le P_{gs}^{t} + P_{s}^{t} \quad (33)$$

where is the gas production at moment t, and is the gas load demand.

IV. Example Analysis

In this paper, data are taken from an integrated energy system park in the north, the mathematical model of IES is developed by YALMIP and the optimization function is solved in MATLAB (2022A) using GUROBI.

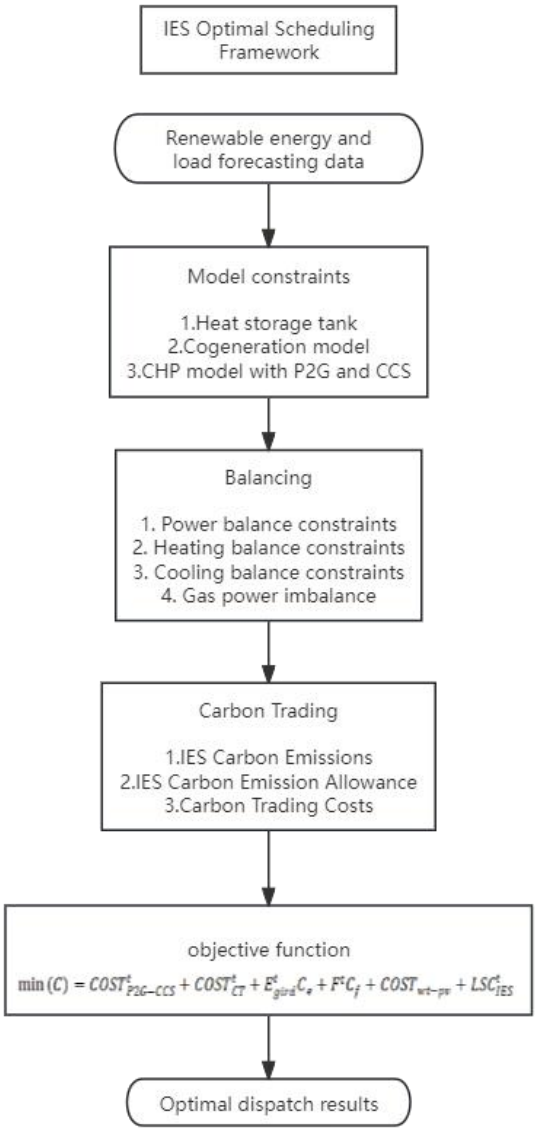


Fig. 2. Step-by-step diagram

A. CCHP Operation Mode Selection

The figure shows the comparison of the results of FTL and FEL optimization objectives. As can be seen from the comparison of the figure, the FEL model is significantly better than the FTL model under the two optimization objectives of fuel, power cost, and carbon trading emissions. If the CHP unit adopts the FTL model, it will seriously limit the accommodation of renewable energy. Therefore, all CCHPs in the next optimization model adopt the FEL operation mode.

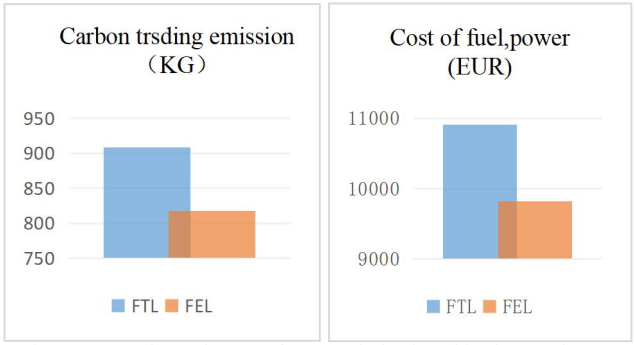


Fig. 3. Comparison of FTL and FEL optimization objective results

B. Comparison of Scheduling Models

To verify the effectiveness of the proposed P2G + CCS model and the optimal scheduling framework based on IES carbon trading, four optimization models are proposed and compared around wind and PV power generation capacity, CO2 emissions, and operating costs. The four optimization models are as follows:

Model 1: CCHP without P2G, CCS and carbon trading.

Model 2:CCHP + P2G without CCS and carbon trading.

Model 3: CCHP with P2G + CCS without carbon trading.

Model 4: CCHP + P2G + CCS + Carbon Trading.

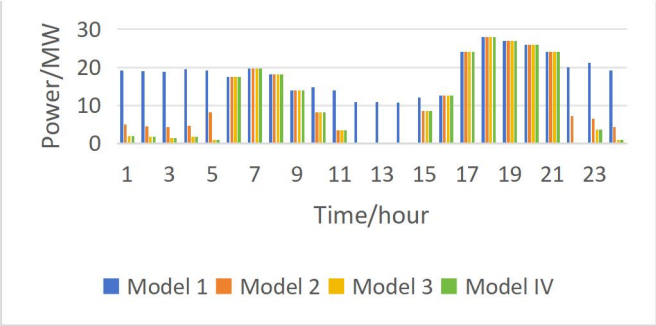


Fig. 4. Comparison of power output of cogeneration models

The figure shows the comparison of the output power of the CHP model. Comparison of Model 2 and Model 1 shows that the grid power provided by the CHP unit decreases during high renewable energy generation hours. It can be seen that P2G transmits the power from the CHP unit and reduces the grid power provided by the CHP unit. Comparison between Model 3 and Model 2 shows that the grid-connected power provided by the CHP unit further decreases at high wind levels. It can be seen that the CO2 captured by the CCS consumes the power of the CHP and reduces the grid power provided by the CHP unit. During the period of high PV power, the CHP unit does not provide grid-connected power due to low heat load demand and the CHP unit outputs less power, all of which is converted to natural gas by P2G. Comparing Model 4 and Model 3, carbon trading does not affect the output of the CHP unit.

Comparison plot of IES operating costs. Comparing the operating costs of Model 1, Model 2, and Model 3, it is found

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that without adding a variable, the operating cost decreases due to the fact that cogeneration with P2G and CCS units increases the renewable energy generation and reduces the fuel electricity cost of the IES, and the utilization of the carbon capture system reduces the IES operating cost as well. The difference between Model 3 and Model 4 during the three high renewable energy generation hours of 0:00 - 5:00, 10:00 - 15:00, and 22:00 - 24:00 represents the reduction of IES operating costs through carbon trading. However, during the low renewable energy generation hours of 6:00 - 9:00 and 16:00 - 21:00, the cost of renewable energy units is lower than the cost of coal-fired and natural gas-fired units for purchasing carbon allowances through carbon trading, which increases the operating cost of IES.

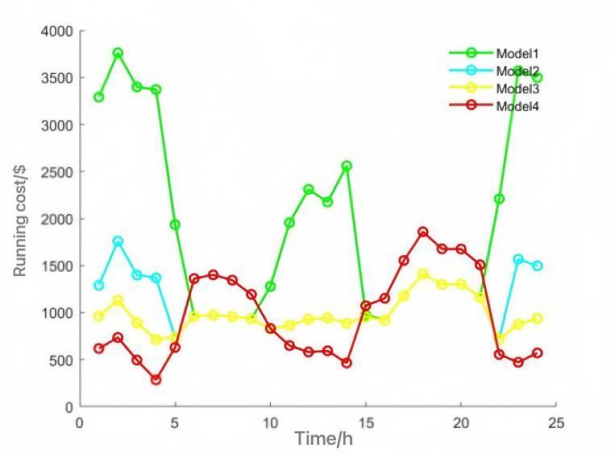


Fig. 5. Comparative economics

The figure shows the comparison of CO2 emissions of the four models. Model 2 reduces its emissions compared to Model 3 because CCS is used to capture part of the CO2 into the P2G for recycling.

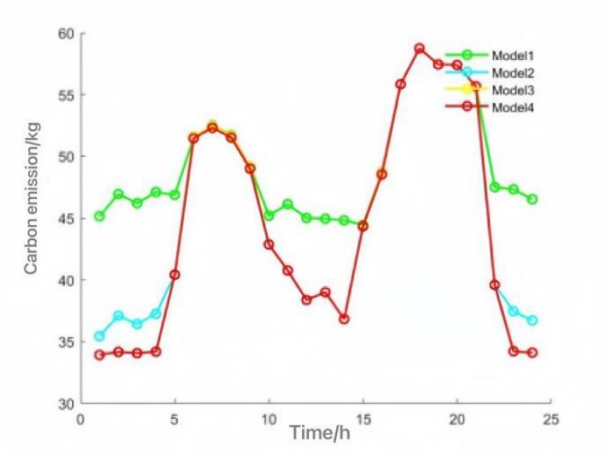


Fig. 6. Comparison of carbon emissions

A comparison of the four models for PV power regulation is given in Fig. Model 1 enhances PV power regulation with cogeneration with P2G as compared to model 2. P2G can take the responsibility of generation and provide redundancy for PV power packages. Comparison of Model 2 with Model 3 shows that CCS does not affect PV power regulation. During the 10:00 - 14:00 time period, there is a situation where there is less heat demand and more cold demand, and at this time the CHP generation is reduced. Considering the minimum output power limit of the CHP with P2G and CCS units, it is found that CCS does not facilitate the conversion of P2G and does not enhance the regulation of PV generation.

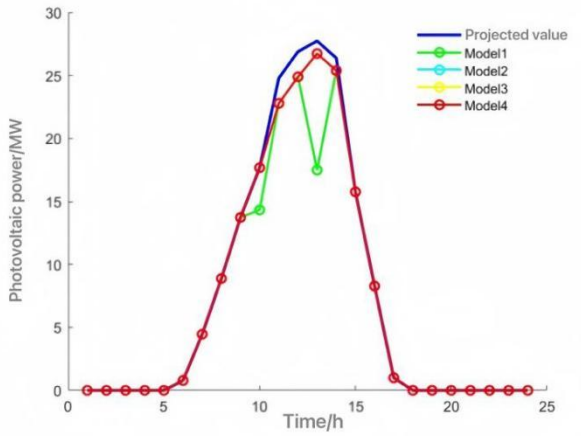


Fig. 7. PV power dissipation in the IES

The following figure gives a comparison of wind power regulation for the four models. During 0:00 - 5:00 and 22:00 - 24:00 wind power high power hours, Model 1 compared to Model 2 shows that cogeneration with P2G enhances the wind power regulation due to the fact that P2G can convert electricity to natural gas, which provides energy redundancy for wind power regulation. Model 3 compared to Model 2 shows that cogeneration with P2G and CCS units enhances the wind power adaptability due to the fact that CCS provides CO2 to P2G, which reduces the operating cost of P2G, which in turn facilitates the conversion of P2G and enhances the wind power adaptability. The CCS also requires a large amount of cogenerated electricity in its operation. Comparison of Model 4 and Model 3 reveals that carbon trading does not affect wind power regulation.

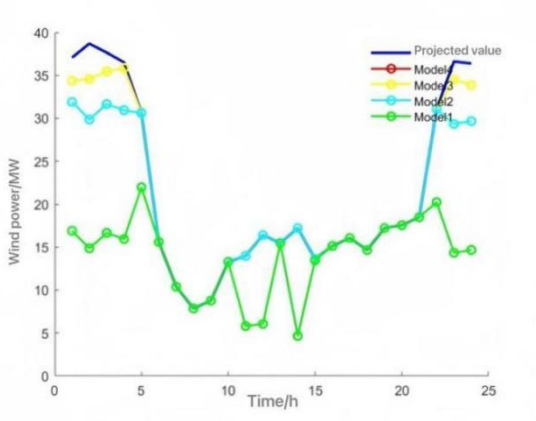


Fig. 8. Wind power dissipation in the IES

Combining the data of renewable energy consumption ratio, CO2 emission and IES operation cost in the table. It can be seen that Model 4 is well optimized for IES operation. This is because the P2G unit can consume excess wind power to generate natural gas to supply the gas turbine, which can

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reduce part of the integrated cost, and is more effective in terms of economic cost; when both the heat pump and P2G unit are added, the integrated cost of the system is greatly reduced, which greatly improves the system's ability to consume wind power. In addition wind turbines and PV units have no carbon emissions and all carbon allowances can be sold. Carbon trading increases the operating costs of CHP units and micro gas turbines. However, the proceeds from the sale of carbon allowances by renewable energy sources are higher than the cost of purchasing carbon allowances for CHP and micro-gas turbines, thus lowering the overall operating costs of the IES.

TABLE I. COMPARISON OF RESULTS

model	wind power consumption	Photovoltaic Consumption	Carbon dioxide emissions (kg)	(manu facturing, production etc) costs
Model 1	57.61%	68.74%	954.5	46372.6
Model 2	79.32%	90.12%	954.5	30882.9
Model 3	88.20%	90.13%	808.3	26084.7
Model 4	88.20%	90.13%	808.3	17544

ACKNOWLEDGMENT

This paper is funded by the Power Grid Planning and Research Center of Guizhou Power Grid Co., Ltda. (Contract number: GZKJXM20222391)

REFERENCES

[1] Y. Jiangsheng, Low Carbon Economy Dispatch of Integrated Energy Systems for Accounting and Demand Response. Anhui University of Technology, 2023.

[2] D. Xianbo, T. Sumeng, L. Shubo, "Integrated energy system day-ahead-intraday multi-objective optimal control strategy," Electrical Measurement and Instrumentation, vol.57(16), pp. 109-117, 2020.

[3] Lorestani A, Ardehali MM, Optimization of autonomous combined heat and power system including PVT, WT, storages, and electric heat utilizing novel evolutionary particle swarm optimization algorithm. Renew Energy, 2018.

[4] L. Zhuoran, Z. Xiaodong, W. Shouxiang, "Optimal scheduling of an integrated electricity-heat energy system considering thermal network dynamics and carbon trading," Journal of Power Systems and Automation, vol.34, pp. :64-70, 2022.

[5] X. Min, L. Yanxuan, Y. Jianan, "Low-carbon optimal scheduling of an integrated urban energy system coupled with electricity-hydrogen-hybrid natural gas," Power automation equipment, vol.1(20), 2023.

[6] Y. Ting, L. Hao, W. Jin, "Deep Reinforcement Learning Based Low Carbon Economy Dispatch of Integrated Energy System in Parks," Grid technology, in press.

[7] Chen Z, Zhang Y, Ji T, Cai Z, Li L, Xu Z. "Coordinated optimal dispatch and market equilibrium of integrated electric power and natural gas networks with P2G embedded," Modern Power system Clean Energy, vol.6(3), 2018.

[8] Blanco H, Faaij A. A review at the role of storage in energy systems with a focus on power to gas and long-term storage. Renew Sustain Energy Rev, 2018.

[9] Z. Binning, W. Jiangpeng, Z. Lei," Optimal scheduling of integrated energy systems considering electricity-to-gas and gas-grid hydrogen injection technologies," Modern power, in press.

[10] M. Ming, M. Siyuan, Z. Huiting, "Two-tier optimal operation strategy of an integrated energy system containing a coupled photovoltaic power plant and CCS-P2G," Journal of North China Electric Power University (Natural Science Edition, in press.

[11] L. Weidong, Z. Libing, Q. Dawei, "Day-ahead optimal scheduling of an integrated electricity-gas energy system considering zero carbon emission," Journal of Solar Energy, vol.44(06), 2023.

[12] H. Wenxuan, L. Daobing, L. Shichun, "Two-tier optimisation of an integrated energy system with P2G and demand response under a dual carbon objective," Electrical Measurement and Instrumentation, vol.59(11), 2022.

[13] Ni L, Liu W, Wen F, Xue Y, Dong Z. Optimal operation of electricity, natural gas and heat systems considering integrated demand responses and diversified storage devices. Modern Power Systems and Clean Energy , vol.6(3), 2018.

[14] He L, Lu Z, Zhang J, Geng L, Zhao H, Li X. Low-carbon economic dispatch for electricity and natural gas systems considering carbon capture systems and power-to-gas. Apply Energy, 2018.

[15] Zhou Y, Hu W, Min Y, Dai Y. Integrated power and heat dispatch considering available reserve of combined heat and power units. IEEE Trans Sustain Energy, vol. 10(3), 2019.

[16] Martínez Cesena EA, Mancarella P. Energy systems integration in smart districts: robust optimisation of multi-energy flows in integrated electricity, heat and gas networks. IEEE Trans Smart Grid, vol. 10(1), 2019.

[17] Wang Y, Wang Y, Huang Y, Yu H, Du R, Zhang F, et al. Optimal scheduling of the regional integrated energy system considering economy and environment. IEEE Trans Sustain Energy, vol. 10(4), 2019.

[18] Cheng Y, Zhang N, Wang Y, Yang J, Kang C, Xia Q. Modeling carbon emission flow in multiple energy systems. IEEE Trans Smart Grid , vol. 10(4), 2019.

[19] Wang Y, Qiu J, Tao Y, Zhao J. Carbon-oriented operational planning in coupled electricity and emission trading markets. IEEE Trans Power System , vol. 35(4), 2020.

[20] Li F, Qin J, Kang Y. Closed-loop hierarchical operation for optimal unit commitment and dispatch in microgrids: a hybrid system approach. IEEE Trans Power System , vol. 35(1), 2020.

[21] Dai Y, Chen L, Min Y, Mancarella P, Chen Q, Hao J, et al. Integrated dispatch model for combined heat and power plant with phase-change thermal energy storage considering heat transfer process. IEEE Trans Sustain Energy , vol. 9(2), 2018.

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