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Low-Carbon Optimization Scheduling of Integrated Energy Based on Offshore Wind Power Hydrogen Production and Onshore Ammonia-Blended Combustion

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Abstract

Under the promotion of the "dual carbon" policy, offshore wind power and other renewable energy sources have ushered in rapid development. As an innovative solution, offshore wind hydrogen production technology provides a new pathway for achieving low-carbon and efficient operation of offshore Integrated Energy Systems (IES). At the same time, ammonia, as an energy source with high energy density and good storage capabilities, can facilitate the low-carbon and efficient use of thermal power generation. With sufficient ammonia penetration into the integrated energy system, ammonia storage can be considered to coordinate the ammonia production process. However, the system's ammonia usage usually requires hydrogen coordination for preparation, which poses a challenge to the operation of onshore integrated energy systems. To address this issue, this paper proposes a low-carbon optimization dispatch for integrated energy systems based on offshore wind hydrogen production and onshore ammonia synthesis. Firstly, by studying the operational mechanisms of offshore wind power and hydrogen technology and comprehensively considering the offshore system's grid connection, an offshore wind hydrogen production system and its operation modes are established. Secondly, considering the large-scale hydrogen transport to onshore integrated energy systems, the hydrogen-to-ammonia conversion process and ammonia usage process are optimized. A technological framework is proposed for hydrogen-coordinated ammonia production, which also involves ammonia co-firing with thermal power units. Finally, with the objective of minimizing the total operational cost, the feasibility of the integrated energy system is verified through simulation analysis. The results show that the proposed model can effectively improve energy utilization efficiency, significantly reduce the economic cost of the system, and offer clear low-carbon economic benefits.

Keywords

Offshore Wind Power Hydrogen Production, Multi-Energy Storage, Multi-Utilization of Hydrogen Energy, Ammonia Blending Combustion in Thermal Power Generation

1. Introduction

As global environmental pollution worsens and China's "dual carbon" goals are set, transforming the energy structure and achieving a low-carbon economy have become urgent priorities. Offshore wind power, a clean and renewable energy source with abundant potential and high energy conversion efficiency, is a key focus for China's renewable energy development. To achieve low-carbon integrated energy systems, alongside promoting green renewable energy, the diversified use of hydrogen energy is considered an ideal solution. By combining offshore wind power with hydrogen production technology, an offshore wind hydrogen production system can stabilize wind power fluctuations, improve wind power absorption, and help transition to a low-carbon economy.

Numerous studies on offshore wind power hydrogen production have been conducted internationally. Combining offshore wind power platforms with hydrogen technology can enhance wind power absorption and reduce output volatility. Literature [1] analyzed the current status and trends of offshore wind power hydrogen production. Literature [2] explored various operation modes of offshore wind-hydrogen systems and optimized capacity configurations for each mode. Offshore wind power hydrogen production is crucial for enabling offshore wind platforms to move into deeper seas and is a key source of green hydrogen for land-based use.

Some studies have also explored hydrogen production from offshore wind power and its role in integrated energy systems. Literature [3] proposed an optimization method for a wind power hydrogen production system, effectively reducing costs and promoting wind power consumption. Literature [4] proposed a robust optimization scheduling model for multi-energy microgrids, considering offshore wind power hydrogen production. Literature [5] established an optimization model for offshore wind power-hydrogen systems, comparing various configurations and highlighting the economic viability of this model over traditional hydrogen production systems.

Currently, thermal power remains the main power source in integrated energy systems (IES), which brings challenges to carbon emissions. Reducing emissions from thermal power is key to the low-carbon transformation of energy systems. Ammonia, a zero-carbon energy source, has a comparable calorific value to coal and is more economical for storage than hydrogen [6]. Literature [7] analyzed the impact of electro-to-ammonia and ammonia blending combustion technologies on the wind-solar-fire system and verified the effectiveness of the integrated energy system with ammonia storage. Ammonia blending combustion technology in thermal power units is already an effective method to reduce carbon emissions [8]. The offshore wind power platform's hydrogen production can be utilized for ammonia production, contributing to emission reduction in IES.

This paper proposes a low-carbon optimization scheduling of integrated energy based on offshore wind power-to-hydrogen production and onshore ammonia synthesis. The coordinated operation of hydrogen utilization, including ammonia synthesis, ensures full ammonia combustion in thermal power units for low-carbon operation. A model for offshore wind power-to-hydrogen production and hydrogen transportation was developed, and integrated with the onshore energy system for multiple hydrogen uses. Stored hydrogen is converted into ammonia for thermal power units, reducing carbon emissions. The problem is formulated as a mixed-integer linear programming (MILP) problem and solved using CPLEX, aiming to minimize overall operational costs.

2. Operation Characteristics and Modeling of Hydrogen Production and Transmission System for Offshore Wind Power Generation

2.1. The Structure of Hydrogen Production at Sea and Ammonia Production through Hydrogen Storage on Land

Figure 1 shows the schematic diagram of offshore wind power for hydrogen production and onshore hydrogen storage for ammonia production.

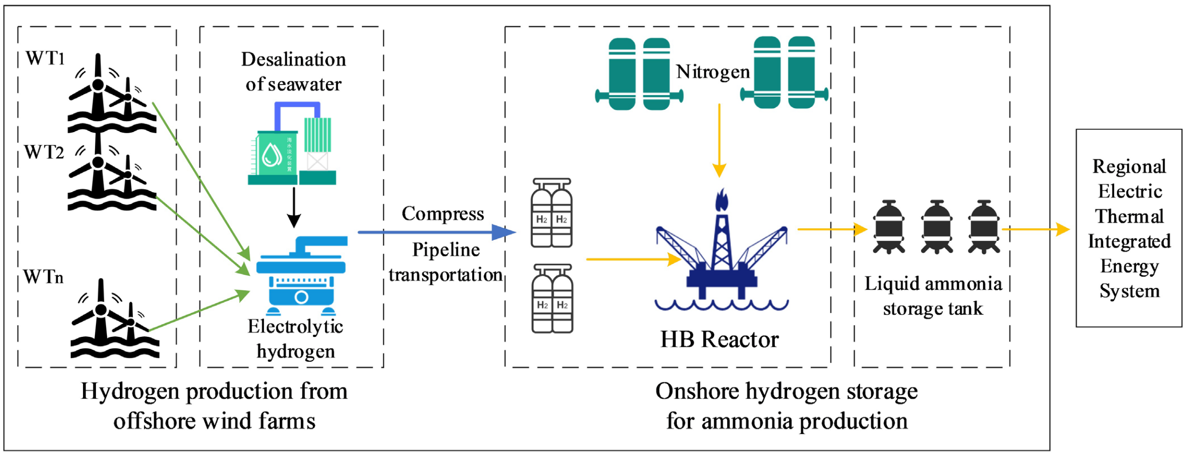

Figure 1. Schematic diagram of hydrogen production from offshore wind power and ammonia production from onshore hydrogen storage.

2.2. Mathematical Model of Offshore Wind Power for Hydrogen Production

Wind power generation is mainly utilized for subsequent hydrogen production, providing power sources for the hydrogen transmission system. Based on the current research on wind power generation technology, the relationship between wind power generation capacity and wind turbine units can be obtained as follows:

$$P_{\mathrm{WF}}=\begin{cases}\dfrac{P_W^N v^3}{v_W^{N3}-v_{in}^3}-\dfrac{P_W^N v_{in}^3}{v_W^{N3}-v_{in}^3}, v_{in}\le v\le v_W^N\\ \dfrac{1}{2}\eta_F\rho_K B_W F_p v^3, v_W^N< v\le v_{out}\end{cases} \tag{1}$$

P_{WF} —the output power of the wind turbine

η_F —the efficiency of the wind turbine

B_{W} —the radius of the wind turbine blades

3. Model Construction of Comprehensive Energy System Incorporating Offshore Wind Power for Hydrogen Production

Ammonia energy storage is ideal for converting and storing the unstable electrical energy of offshore wind power as chemical energy, enabling long-term storage.

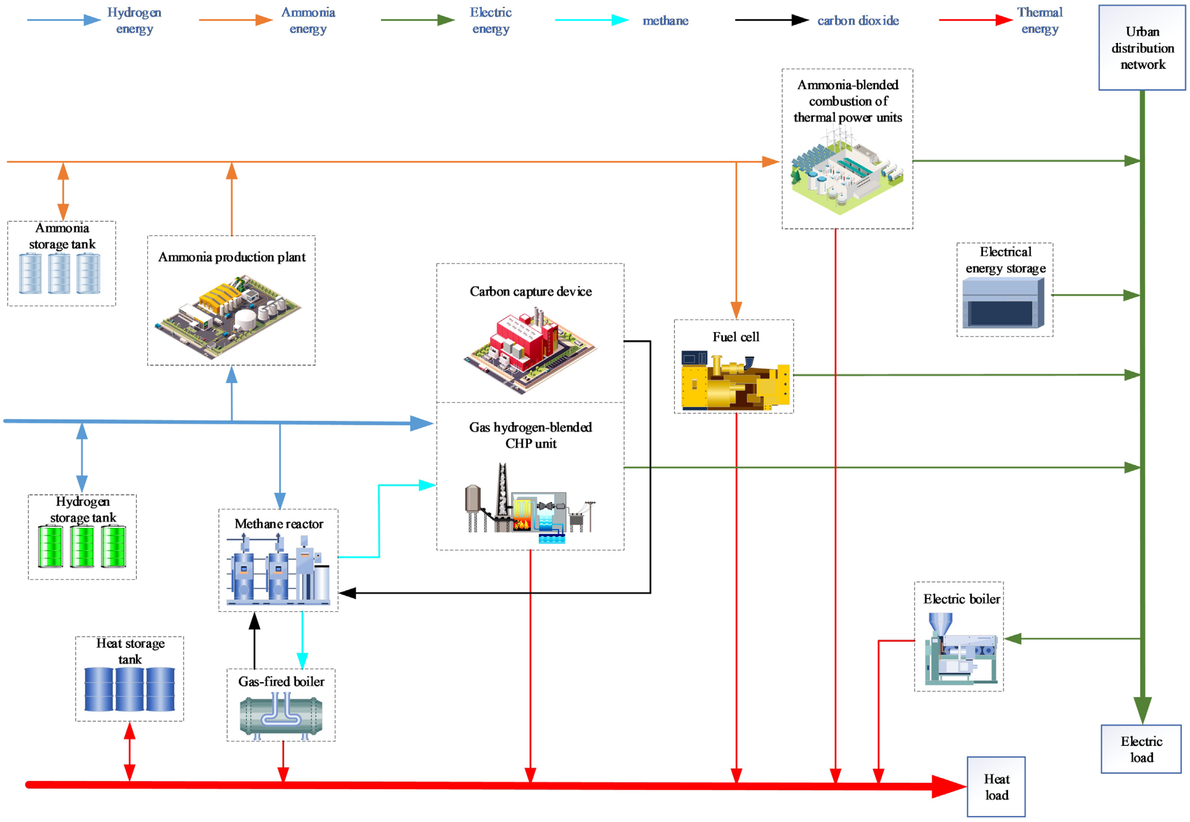

Figure 2. Comprehensive energy system framework of multiple utilization of hydrogen energy and hydrogen ammonia production.

As shown in Figure 2, hydrogen produced by offshore wind power is transported via pipelines to the onshore integrated energy system. It serves as raw material for methane reactors and hydrogen-blended CHP units powered by natural gas. Excess hydrogen can be stored or used for ammonia production. The ammonia is then utilized for ammonia-blended combustion in thermal power units and as fuel cell material. Hydrogen and ammonia storage tanks are included to address the uncertainty of offshore wind power production and ensure stable system operation by controlling hydrogen and ammonia quantities, as the hydrogen production capacity of PEM electrolysis equipment impacts ammonia production.

3.1. Ammonia Storage Unit

$$S_t^{HT} = \left(1-\phi_{q,bat}\right)S_{t-1,HT} + \left[P^{q}_{t,ch}\eta_{q,ch} - P^{q}_{t,dis}/\eta_{q,dis}\right]\times \Delta t \tag{2}$$

S_t^{HT} —The ammonia storage quantity of the ammonia storage tank at time t

$\phi_{q,bat}$ —Self-release ammonia loss rate

$\eta_{q,ch}$ —Hydrogen filling efficiency

$\eta_{q,dis}$ —Hydrogen release efficiency

$P^{q}_{t,ch}$ —Hydrogen charging power of hydrogen storage tank

$P^{q}_{t,dis}$ —Hydrogen discharging power of hydrogen storage tank

3.2. Use Ammonia Unit

The ammonia unit is mainly used in ammonia fuel cells and in the operation of thermal power units. For AFC, considering the energy of the battery, it can generate electrical energy and output power. The operation model is as follows:

$$\begin{cases} P_{F,DC} = \dfrac{U_{FN}\varsigma_F V_{\mathrm{NH3}} N_A}{1800 V_m C_0} \\ Q_{DC} = Q_{FH,in}\eta_{C,\mathrm{NH3}} \end{cases} \tag{3}$$

V_{NH3} —The volume of ammonia gas at normal temperature

$\eta_{C,\mathrm{NH3}}$ —Ammonia storage tank ammonia storage efficiency

U_{FN} —Rated output voltage

Q_{DC} —Fuel cell energy

$Q_{FH,in}$ —Input hydrogen fuel chemical energy

ς_{F} —The energy conversion efficiency of the fuel cell is set at 45%

3.3. Other Units

Other units include models of methane reactors and carbon capture systems, etc. The hydrogen produced by offshore wind power is used not only in the ammonia production process and storage but also in the methane reactors and gas-hydrogen blended CHP units.

The methane reactor can mix hydrogen transported from offshore platforms with carbon dioxide to provide the required natural gas for CHP units and gas boilers. The specific model is as follows:

$$\begin{cases} M^{\mathrm{g}}_{t,MR} = \eta_{MR} M^{\mathrm{H_2}}_{t,MR} \\ M^{\mathrm{H_2}}_{\min,MR} \le M^{\mathrm{H_2}}_{t,MR} \le M^{\mathrm{H_2}}_{\max,MR} \\ \Delta M^{\mathrm{H_2}}_{\min,MR} \le M^{\mathrm{H_2}}_{t+1,MR} - M^{\mathrm{H_2}}_{t,MR} \le \Delta M^{\mathrm{H_2}}_{\max,MR} \end{cases} \tag{4}$$

$M_{t,MR}^{\mathrm{H}_2}$ —The amount of hydrogen energy transported by sea and input into MR

$M_{t,MR}^{\mathrm{g}}$ —The output power of natural gas from the MR unit

η^{MR} —The energy conversion efficiency of MR

$M_{\max,MR}^{\mathrm{H}_2}$, $M_{\min,MR}^{\mathrm{H}_2}$ —To determine the upper and lower limits of hydrogen energy input for MR

$\Delta M_{\max,MR}^{\mathrm{H}_2}$, $\Delta M_{\min,MR}^{\mathrm{H}_2}$ —For the upper and lower limits of the climbing slope of MR

Hydrogen production at sea, in addition to large-scale ammonia production, is also used for efficient hydrogen energy utilization. Some hydrogen is introduced into gas-hydrogen blended CHP units to ensure cleaner fuel and reduce environmental impact. Current experiments show that the maximum hydrogen volume ratio blended into natural gas for safe and stable gas turbine operation is 20%. The specific model is as follows:

$$\begin{cases} \varpi_t = \dfrac{P_{t,CHP}^{\mathrm{H}_2}}{F_{\mathrm{H}_2}} \Bigg/ \left(\dfrac{P_{t,CHP}^{\mathrm{H}_2}}{F_{\mathrm{H}_2}} + \dfrac{P_{t,CHP}^{\mathrm{g}}}{F_{\mathrm{CH}_2}} \right) \\ 0 \le \varpi_t \le 20\% \\ P_t^{CHP} = \left(\varpi_t F_{\mathrm{H}_2} + [1 - \varpi_t] F_{\mathrm{CH}_2} \right) \left(\dfrac{P_{t,CHP}^{\mathrm{H}_2}}{F_{\mathrm{H}_2}} + \dfrac{P_{t,CHP}^{\mathrm{g}}}{F_{\mathrm{CH}_2}} \right) \end{cases} \tag{5}$$

ϖ_t —Hydrogen blending ratio of gas

$P_{t,CHP}^{\mathrm{H}_2}$ —The hydrogen gas input to the CHP unit through the hydrogen blending device for gas

$P_{t,CHP}^{\mathrm{g}}$ —The power of natural gas input to the CHP unit through the hydrogen-blended natural gas injection device

P_t^{CHP} —The total power of the mixed gas of the CHP unit

F_{H_2} —The lower calorific value of hydrogen gas

F_{CH_2} —The lower calorific value of natural gas

F_{mix} —The lower calorific value of the mixed gas

In the CHP unit equipped with carbon capture devices [9] [10], the electricity generated is used in two places. One part is supplied to the carbon capture device for its operation, and the remaining part is used for other electrical equipment. The specific model is as follows:

$$\begin{cases} P_{cct} = P_{CHP}^{f} - P_{qt}^{E} \\ P_{cct} = L_B^{CCT} + \eta_{CCT} \lambda_t^{CCT} Q_p^C \\ Q_p^C = \vartheta_C P_{chp}^{f} \end{cases} \tag{6}$$

P_{cct} —Power consumption for carbon capture

P_{CHP}^{f} —The generating power of the CHP unit

P_{qt}^{E} —The net output power of the carbon capture unit

L_B^{CCT} —Base energy consumption power

η_{CCT} —The energy consumed by the carbon capture unit when capturing CO_2

in the carbon capture unit system

Q_p^C —Carbon emissions

λ_t^{CCT} —The carbon capture efficiency of the carbon capture unit

ϑ_C —The unit carbon emission intensity of the carbon capture unit

4. Modeling and Solving the Problem

4.1. Objective Function

The low-carbon scheduling model for offshore wind power and onshore ammonia synthesis aims to minimize total operating costs while considering the operation and maintenance of energy storage devices. It optimizes day-ahead scheduling and backup plans for offshore wind power hydrogen production, onshore hydrogen consumption, ammonia synthesis, thermal power units, and carbon capture devices.

The formula for the total operating cost of the system is as follows:

$$C_T = C_{PE} + C_{LM} + C_{TP} + C_{CC} + C_{CE} \tag{7}$$

4.2. Case Study Analysis

This paper presents the IES low-carbon optimization scheduling test system, consisting of the IEEE-33-node power system and the 23-node thermal system. The problem is solved using MATLAB 2021a with the Gurobi solver via the Yalmip toolbox, with a 24-hour scheduling period. Four scenarios will be analyzed for the low-carbon optimization scheduling model based on offshore wind power hydrogen production and onshore ammonia synthesis:

- The offshore wind power system does not include hydrogen production units, the integrated energy system does not include ammonia synthesis units, and carbon capture or ammonia co-firing in thermal power units is not considered.
- The offshore wind power system includes hydrogen production units, while the onshore integrated energy system does not include ammonia synthesis units, and ammonia co-firing in thermal power units is not considered.
- The offshore wind power system includes hydrogen production units, the onshore integrated energy system includes ammonia synthesis units, and ammonia co-firing in thermal power units is considered.
- Offshore wind power with hydrogen production units, and onshore integrated energy with ammonia production units, while taking into account carbon capture and the ammonia blending ratio of thermal power units.

4.3. Result Analysis

An analysis was conducted on the four aforementioned scenarios. The optimization results for each scenario are presented in the table below.

As shown in Table 1, Scenario 4 has the lowest total operating cost, 42.93%, 25.23%, and 9.48% lower than the other scenarios, respectively. This indicates that the introduction of hydrogen and ammonia units has improved new energy consumption capacity and economic efficiency.

In terms of carbon emissions, Scenario 4 shows a significant reduction compared to the other scenarios, with reduction rates of 49.96%, 48.36%, and 40.01%, respectively. This highlights the advantages of the proposed comprehensive energy system optimization in achieving low-carbon benefits.

Table 1. Optimization results of four scenarios.

Scene	Total operating cost	Purchase cost	Equipment depreciation and maintenance costs	Cost of coal consumption for the operation of thermal power units	Cost of carbon capture	Carbon emission cost
one	78.5227	47.4857	7.3783	0	0	23.6587
two	59.9297	29.9104	10.8607	0	3.6916	15.4670
three	49.5049	10.6955	3.2404	25.7129	4.4756	5.3808
four	44.8095	4.7251	4.1475	28.7203	5.2187	1.9979

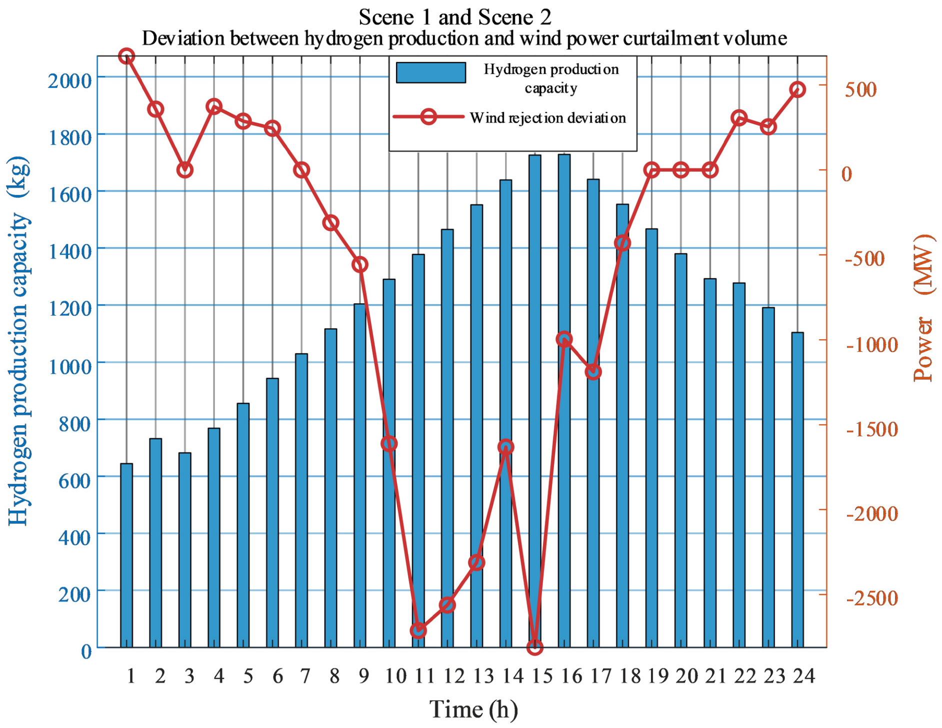

Figure 3. Deviation of hydrogen output and abandoned wind power in Scenario 1 and Scenario 2.

Scenario 1 directly integrates offshore wind power into the energy system, causing high wind power discard and electricity purchase costs during shortages. In contrast, Scenario 2 incorporates offshore wind power hydrogen production, including production, transmission, and storage, which reduces wind power discard by 18% and lowers electricity purchase costs. This demonstrates that offshore wind power hydrogen production technology lowers operating costs and enhances renewable energy utilization.

As shown in **Figure 3**, Scenario 2 reduces wind power discard by about 18% compared to Scenario 1. Scenario 1 does not produce hydrogen, and the hydrogen production values in **Figure 3** are from Scenario 2. During the periods from 1:00 to 7:00 and 19:00 to 24:00, the difference in wind power discard is positive, indicating that the output devices in Scenario 1 are increasing. The difference between predicted and actual wind power utilization shows an overall downward trend, but during most periods, the difference in wind power discard is negative, as the electricity load demand is higher during the daytime. Compared to Scenario 1, during the 8:00 to 19:00 period, the electricity load demand is high, and the wind power discard is much lower than in the morning and evening. Therefore, Scenario 2, with offshore wind power hydrogen production, compresses the excess electricity into hydrogen and transports it to the land, greatly reducing wind power discard during this period. Scenario 2 can also store excess hydrogen in onshore storage tanks and release it when electricity demand is higher, such as from 10:00 to 11:00 and 19:00 to 20:00. However, compared to Scenario 1, more energy (electricity and thermal energy) needs to be purchased, increasing the purchase cost. Thus, compared to Scenario 1, Scenario 2 reduces wind power discard but still experiences it, while the total cost is relatively lower.

Analysis of the Impact of Ammonia Production on Thermal Power Plant Systems:

Scene 3 has a total operating cost reduction of approximately 17.4% compared to Scene 2. Scene 2 does not have a coal-fired power plant with ammonia blending combustion. The coal consumption costs of the coal-fired power plants in Scene 2 are all generated by Scene 3. Scene 3 has configured an ammonia utilization link on the basis of Scene 2, which requires more hydrogen consumption. However, it reduces carbon emissions in coal-fired power generation and reduces carbon emissions by approximately 13.92% during the entire ammonia blending combustion process, demonstrating the effectiveness of the ammonia blending combustion link of the coal-fired power plants in the integrated energy system in reducing carbon emissions.

Compared with Scenarios 1 and 2, Scenarios 3 and 4 have introduced ammonia blending combustion in thermal power units. Due to the increase in ammonia production, the use of thermal power units has been promoted, and the carbon emissions of thermal power generation have been reduced. The output curves are shown in **Figure 4**. In most time periods, the output situations of Scenarios 3 and 4 are similar and show an upward trend overall. During the 9:00 - 12:00 period, considering the hydrogen production situation in Scenario 2, the demand for electricity load is greater, and a large amount of hydrogen is released for use in CHP units. The output situation of thermal power units shows a slight decrease in process. The thermal energy scheduling results are shown in **Figure 4**. The thermal power units in the integrated energy system are mostly cogeneration units. During their operation, they release heat to provide heat load for the entire system and also reduce the heating energy consumption of the system. While enhancing the flexibility of system heating, it also promotes the system to generate further economic benefits.

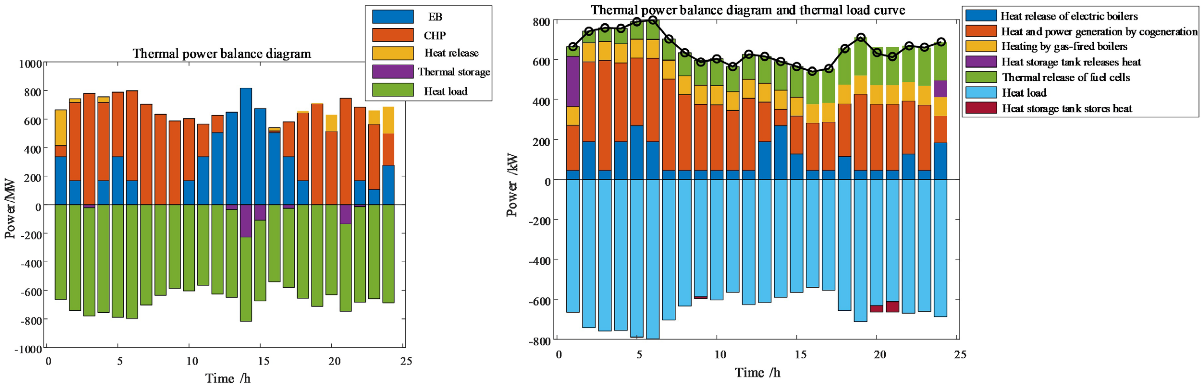

Figure 4. Heat scheduling results in scenario 3 and scenario 4.

5. Conclusions

1) Regarding the operation mechanism of the offshore wind power hydrogen production platform, it is connected to the onshore integrated energy system. By integrating green hydrogen and hydrogen-ammonia processes, the flexible regulation capacity of the integrated energy system is enhanced. This enables the effective utilization of renewable energy from offshore platforms and improves the absorption capacity of renewable energy.

2) This integrated energy system fully and flexibly utilizes hydrogen and ammonia energy. The total cost of the system is reduced by approximately 42.93%. Since this paper considers the integration of offshore wind power hydrogen production into the integrated energy system, it can better realize the power consumption absorption capacity of the wind farm, and the wind power outage rate is reduced by about 27%. The utilization of hydrogen and ammonia energy leads to a decrease of approximately 49.96% in the carbon emissions of the system, verifying the effectiveness of introducing the offshore wind power hydrogen production link in the system for carbon reduction and cost saving. It is of great significance for achieving a low-carbon integrated energy system.

3) Utilizing ammonia-blended combustion in thermal power units for power generation further reduces the carbon emissions and economic costs of the system. It is particularly important to note that this study does not cover the construction costs of facilities such as submarine pipelines, hydrogen energy units, and carbon capture, nor does it consider the coordination and optimization issues over multiple time scales. Further research in this area will be conducted in the future.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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