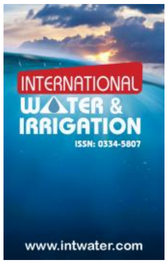

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Energy Scheduling and Low-carbon and Water Conservation Optimization for Electricity-Heat-Cooling-Gas Multi-Region Integrated Energy System

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Abstract: As global demand for green and clean energy grows, integrated energy systems (IESs) capable of integrating renewable energy sources such as photovoltaics and wind power are considered as a key approach to solve the energy crisis. These systems can significantly improve energy efficiency and reduce the use of fossil fuels. This article proposes an energy dispatch and low-carbon optimization method for a multi-region electricity-heat-cooling-gas IES. The method considers traditional energy flows such as electricity and natural gas, while further introducing cooling and heating loads, energy storage technologies (e.g., battery storage and thermal storage), and demand response strategies to more comprehensively simulate the operational characteristics and interactions of energy systems across different regions. Through multi-region collaborative optimal scheduling, the IES achieves energy complementarity and balance between regions, and can flexibly respond to changes in different load demands, thereby enhancing the reliability and resilience of the system. Simulation results show that the proposed method not only improves energy utilization but also significantly reduces operating costs and carbon emissions. Especially with the integration of renewable energy sources, it effectively reduces greenhouse gas emissions, contributing to global environmental protection and sustainable development goals. In addition, by incorporating efficient water management strategies into the multi-region IES, the system further supports environmental protection through reduced water consumption, aligning with both energy and water conservation goals.

Keywords- Multi-region integrated energy system; Energy scheduling; Low-carbon optimization, Water conservation

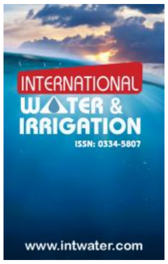
1. Introduction

With the continuous progress of energy system development in low-carbon technology and sustainability, IESs can provide an organic energy supply and integrated system that coordinates energy supply and environmental issues. technology and sustainability [1], IES can provide an organic energy supply and integrated system that coordinates energy production, transmission, distribution, conversion, energy use and energy efficiency. In this context, electricity-heat-cooling-gas multi-IESs have attracted much attention. By integrating different forms of energy and helping to coordinate and optimize the relationship between different energy sources, IES can maximize the use of energy resources, reduce the cost of energy production and consumption [2]. IES can provide an organic energy supply and integrated system that coordinates energy production, transmission, distribution, conversion, energy use and energy efficiency. In this context, electricity-heat-cooling-gas multi-IESs have attracted much attention. By integrating different forms of energy and helping to coordinate and optimize the relationship between different energy sources, IES can maximize the use of energy resources, reduce the cost of energy production and consumption [3], and have the significant advantages of improving energy efficiency, reducing environmental impacts, and enhancing the resilience of energy systems.

Several studies have been made on scheduling optimization of IES and gradually modernizing the traditional IES. Stennikov et al, in article [4] discussed the principle of designing IES using digital twin technology which uses virtual space to simulate various IES configurations in order to find the optimal solution. Odamov, in article [5] in the development of energy systems combining smart power networks and digital technologies to change the traditional IES in order to modernize the IES. Fan in article [6] presented a article on dynamic multi-stage planning approach for IES proposes a model that considers the stages of IES development and how to optimize the configuration and expansion of the energy system according to the different stages of development. Although current studies have incorporated modern technologies into IES, these studies have mainly focused on single-region IESs. While these single-region IESs have improved the efficiency of energy use and system reliability in the region to some extent, they still have some limitations. Single-region IESs may not be able to take full advantage of energy complementarities between different regions, especially in the face of wide-ranging energy demand and supply uncertainties. In contrast, the joint operation of multi-regional IESs can further enhance the efficiency of the energy system across the region. By interconnecting multi-regional IESs, cross-regional energy deployment and optimization can be achieved, taking advantage of the differences in energy supply and demand between different regions and enhancing the flexibility and robustness of the system. By optimizing and scheduling Integrated Energy Systems (IES), energy utilization can be effectively improved, while reducing greenhouse gas emissions [7]. Articles [8] and [9] describe a carbon trading model involving renewable energy sources, respectively.

For the article of multi-region IESs, Zhou et al, in article [10] focus on the operation optimization of multi-region IESs when considering flexible demand response for power and thermal loads, which establishes a mixed integer linear programming model to achieve coordinated distribution of thermal energy among different zones and effectively reduces the peak-to-valley difference of loads through demand response. Article [11] proposed a distributed and collaborative optimization method for multi-region IES based on edge computing units. This approach can reduce the cost of communication facility construction while ensuring data security and privacy. However, as the number and type of coupled devices increase, the computational complexity and the cost of data transmission and storage also increase significantly. Article [12] proposes a coordinated optimization approach for supply and demand in a multi-region IES to balance the long-term overall objectives and the independence of participants such as users and subsystems. The main contributions of this work include the development of a multi-agent model-based optimization methodology for the design and operation of multi-regional IESs that incorporates long-term annual objectives (e.g., annual carbon emissions) into distributed optimization. The current research has made significant progress in multi-region IESs, particularly in the optimization of system architecture and operational strategies.

This article proposes a multi-region IES model that will introduce multiple loads, with the aim of exploring and optimizing the design and operation of an IES more comprehensively. Such a model would not only consider traditional electricity and natural gas energy flows, but would also focus on other types of energy demand such as cooling and heating loads. Through this approach, the interaction of the energy system across different zones and different energy load types can be more effectively modelled and optimized, thereby improving the energy efficiency and reliability of the overall system. Within this framework, strategies for the deployment and optimization of multiple energy loads will be explored, how to utilize energy complementarities between different regions, and how to respond to changes in the demand of various loads, leading to more flexible and efficient energy management. The introduction of this multi-region, multi-load IES model will not only provide new perspectives for the design and improvement of future energy systems, but also new tools for understanding and solving challenges in complex energy systems. Through this comprehensive research approach, the diversified and integrated challenges facing the energy sector can be better addressed and the sustainable development of energy systems can be promoted.



2. Multi-Region IES Dispatch Strategy and Modelling

2.1 Operation Mechanism of Multi-Region IES

1）Single IES Architecture

IES is the efficient utilization and optimal scheduling of energy by integrating multiple forms of energy to meet a variety of energy needs such as electricity, heating, cooling, etc. IES provides an assessment framework for achieving sustainable development of energy systems and contributes to the development of the overall energy system [13]. The core objective of IES is to reduce energy wastage and improve energy utilization efficiency through the synergistic management of different forms of energy, which helps to enhance the sustainability of the system, especially in the context of an integrated energy supply. IES integrates electricity, heat, cooling, gases, and other forms of energy are integrated together. While traditional energy systems tend to be single-energy systems, e.g., focusing only on electricity or heat, IESs are able to satisfy more diversified needs through the complementarity of different forms of energy. The single-part structure of the IES studied in this article is shown in Fig.1.

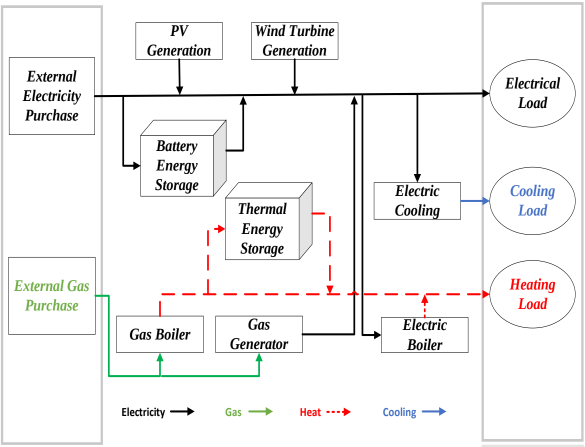


Figure 1: Single-region IES structure

Note: The figure shows the structure of one of the three parts of the IES.

The system in Image 1 contains PV Generation and Wind Turbine Generation as the primary sources of renewable energy. These are combined with the External Electricity Purchase to provide power to the system, and Battery Energy Storage and Thermal Energy Storage are key components that ensure that excess power or heat can be used when needed, increasing the flexibility and stability of the system. Energy is converted to heat within the system by the Electric Boile and Gas Boile; the Gas Generator converts gas to electricity. In addition, the Cooling Load and Electrical Load are regulated by the power supplied by the system. The modelling and optimal scheduling of the carbon cycle IES can be used to achieve low carbon emission targets while maintaining the economics of the system [14]. IES has also considered the carbon emission operation mode of the whole system. In Fig. 1, the carbon emissions generated during the operation of the whole system will be collected by the carbon capture plant (CCP) unit and transported to the nearby carbon storage warehouse to participate in the local carbon trading market.

This structure reduces the dependence on external energy sources and optimizes the efficiency of internal energy use through the synergistic scheduling of multiple energy sources. It demonstrates how multiple energy sources can be effectively integrated on a small scale to achieve the combined use of cooling, heating, electricity and gas [15].

2) Multi-region IESs Architecture

By interacting the three IESs above to form a multifaceted IESs, the structure is shown in Figure 2. The IESs in each region can either operate independently or form an energy network through energy sharing and synergy among multiple regions. There may be temporal and spatial differences in energy supply and demand in different regions, and through inter-regional energy transmission (e.g., electricity, natural gas, etc.), it can deliver excess energy to the peak demand region to avoid the imbalance of energy supply and demand within a single region. Collaborative scheduling between regions can significantly improve the operational efficiency of the system and reduce energy waste. Secondly, the design incorporates renewable energy sources, making the system less dependent on fossil fuels. By optimizing and scheduling resources across regions, it not only improves the utilization of renewable energy sources, but also reduces greenhouse gas emissions such as carbon dioxide, and achieves a more environmentally friendly and sustainable energy development path. Digital twin technology can be used to simulate the configuration of a multi-region IES to find the best solution [16].

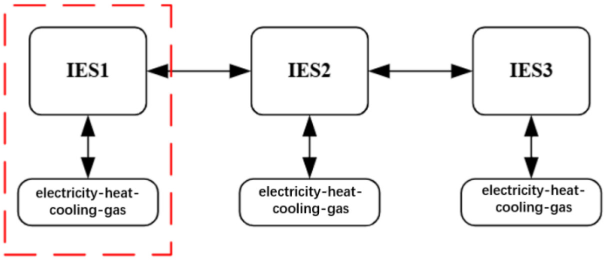
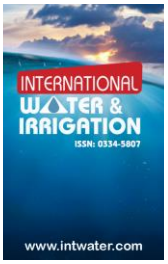


Figure 2: Schematic diagram of a multifaceted IES

Note: The figure shows the structure of the multi-region IESs consisting of three individual IESs

Each region (IES1, IES2, IES3) has a single-region IES structure, which is connected to each other through the electricity network or other energy transmission networks to realize the linkage and coordination of multi-region energy systems. The advantage of this structural design is that energy resources can be shared among different regions to achieve cross-regional balancing of energy supply and demand. For example, when one region has an abundance of wind power and another region has a shortage of energy, the excess power can be shared through the linkage. By optimizing the energy use and scheduling in multiple regions, the operational efficiency of the whole system and the utilization of renewable energy can be further improved, and the dependence on traditional energy sources can be reduced; the coupling of multiple regions makes the system more risk-resistant, e.g., when there are fluctuations in the energy supply in one region, the other regions can provide complementary support to enhance the stability and resilience of the system [17].

In summary, the single-area IES system is characterized by the integrated use of electricity, heat, cooling, and gas as a variety of energy sources to ensure efficient energy management and utilization; the multi-dimensional IES is able to realize collaborative scheduling and optimal utilization of energy between multiple regions on the basis of single IES's through the integration of multiple forms of energy, such as electricity, heat, cooling, gas, etc., which has significantly improved the flexibility and reliability of the energy system. And by reasonably scheduling energy supply and demand between regions, it reduces the system's dependence on a single energy source, and combines renewable



energy and energy storage technologies, making the multiple IES able to respond more effectively to complex energy demand and promote sustainable development and environmental protection.

2.2 Equipment modelling for Diversified IESs (DIES)

1) Gas boilers and electric boilers

Gas boilers and electric boilers produce electricity and heat, respectively, and are modelled as follows, subject to their own operating efficiencies:

$$H_{GB}(t) = \frac{F_{GB}(t)\eta_{GB}}{\Delta T} \qquad (1)$$

$$H_{EB}(t) = \eta_{EB} P_{EB} \qquad (2)$$

In the equation, $H_{GB}(t)$represents the heat power of the gas boiler at time t, F_{GB} represents the gas consumption of the gas boiler at time t, and η_{GB} represents the thermal efficiency of the gas boiler. P_{EB} and$H_{EB}(t)$ represent the power consumption of the electric boiler at time t and the heat power generated at time t, respectively, while η_{EB} represents the thermal efficiency of the electric boiler.

2) Gas generators

The heat generated by the gas generator can be supplied to the IES, thus improving the efficiency of energy utilization. The gas generator produces thermal and electrical power, which is related to the amount of gas consumed and the efficiency of its various functions. Its model can be expressed as:

$$P_{GT(t)} = \frac{F_{GT}(t)\eta_{GT-e}}{\Delta T} \qquad (3)$$

$$H_{GT}(t) = \frac{(1-\eta_{GT-e})F_{GT}(t)\eta_{GT-h}}{\Delta T} \qquad (4)$$

Where $P_{GT}(t)$ and $H_{GT}(t)$ are the electric and thermal power in the gas generator at time t, respectively, $F_{GT}(t)$ is the gas consumption at time t, and η_{GT-e} and η_{GT-e} are the gas generator's generating you but with heat production efficiency, respectively.

3) Refrigeration equipment

The refrigeration equipment is an electric chiller, which provides a cold load related to its refrigeration efficiency η_{EC}.

$$C_{EC}(t) = \eta_{EC} P_{EC}(t) \qquad (5)$$

$C_{EC}(t)$ and $P_{EC}(t)$ are the electric power generated and consumed at time t, respectively.

2.3 Modelling of Distributed Generation Units

1) Photovoltaic modelling

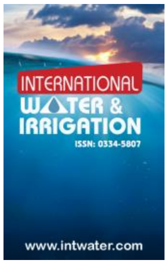
The PV system is modelled based on a typical monocrystalline silicon module. The energy produced by the PV array is proportional to three elements: solar irradiance data, PV system efficiency and area of the PV panels. The PV power output is modelled with respect to irradiance, efficiency and area size as follows [18].

$$P_{PV} = G\xi_{PV} A_{PV} \eta_{PV} \qquad (6)$$

In the equation, P_{PV} is the photovoltaic output power (kW), G is the solar irradiance (W/m²), ξ_{PV} is the local shading factor (fixed at 0.7), A_{PV} is the total area of the solar panels (m²), and η_{PV} is the efficiency factor (approximately 10%).

2) Wind turbine model

Literature [19] kind of considers the wind speed distribution, wind turbine parameters, load distribution and other factors and gives a power output model to calculate the power output of the wind turbine:



$$P_{WT}\begin{cases} 0 & v < v_{cr}, \mathrm{v} \geq v_{co} \\ \frac{v^3 - v_{ci}^3}{v_r^3 - v_{cr}^3} P_r & v_{ci} \leq \mathrm{v} \leq v_{ro} \\ 0 & v_{r<v<}v_{co} \end{cases} \quad (7)$$

P_{WT} is the output power of the wind turbine; P_r is the rated power of the wind turbine; v is the actual wind speed of the wind turbine; v_{ci}， v_{co} and v_r are the cut-in wind speed, cut-out wind speed and rated wind speed of the wind turbine, respectively.

2.4 Modelling of energy storage equipment

1) Battery energy storage model

In smart microgrids, agent-based energy management systems help to optimize the use of battery storage [20]. SOC is a parameter that measures the residual energy of the battery storage, the SOC of the total battery storage composed of each individual battery is consistent with the SOC of the individual battery, there are [21]：

$$SOC(t) = SOC(t-1) + \Delta SOC \quad (8)$$

Included among these，

$$\Delta SOC = \frac{I(t)\Delta t}{Q} \quad (9)$$

In the formula, SOC(t) and SOC(t-1) are the battery storage energy SOC at the beginning of time period t and time period t-1, respectively, and Q is the single battery charge amount. Battery management system (BMS) can effectively improve the efficiency of SOC (surplus charge) management in battery energy storage systems [22].

2) Thermal energy storage system model

Thermal energy storage option Sensible Heat Storage, is through the formula, SOC (t), SOC (t-1) for t time period, t-1 time period at the beginning of the battery storage energy SOC, Q for the single battery charge. Thermal storage method to store thermal energy by heating or cooling liquid or solid storage media, and has the advantages of low cost and relatively safe thermal storage materials, the formula model is as follows [23]:

$$Q_S = \int_{t_i}^{t_f} mC_P \quad (11)$$

Here, Q_S represents the amount of heat stored in Joules, m is the mass of the storage medium in kilograms, C_P is the specific heat in J/(kg·K), t_f and t_i are the starting temperature in °C and the final temperature in °C, respectively.

3. Optimization of scheduling of multifaceted IESs

3.1 Objective function

The objective is to minimize the daily operating cost of the IES, and the cost includes the purchased power cost F_{total} ,the purchased gas cost, and the carbon emission cost [24], without considering other equipment maintenance costs and depreciation rates. The objective function of the optimal scheduling problem is

$$F_{total} = F_{elec} + F_{gas} + F_{Carbon} \quad (12)$$

Included among these，

$$F_{elec} = \sum_{t=1}^{24}\sum_{i=1}^{3} F_{PV}(i,t) + F_{WT}(i,t) + F_{bug}(i,t) - F_{sell}(i,t) \quad (13)$$

$$F_{gas} = \sum_{t=1}^{24}\sum_{i=1}^{3} \lambda_{gas} G_{in}(i,t) \quad (14)$$

$$Z_{Carbon} = P_{Carbon} C_t \quad (15)$$

The cost of purchased electricity is equal to the cost of wind turbine power generation, photovoltaic power generation cost and the sum of the cost of purchased electricity, minus the profit gained from the sale of electricity; G_{in} is the amount of gas purchased at each moment, and λ_{gas} is the price of gas. Z_{Carbon} is the carbon trading cost, P_{Carbon} is carbon price, C_t is time t amount of carbon bought on the carbon market. Multi-region IESs can significantly reduce the operating costs of energy systems through collaborative scheduling, while increasing the efficiency of renewable energy use [25].

3.2 Constraints

1) Power Balance Constraints

Each segment of the IES operation, either unitary or multinomial, the electric power, heat power and cold power need to satisfy the balance. Power balance constraints are critical to ensure stable power system operation, especially when considering wind power and load fluctuations [26].

The first is the electrical power balance, which needs to satisfy that the sum of the photovoltaic power P_{PV} and the wind turbine electrical power P_{WT}, the sum of the purchased power P_{buy} and the power generated by the gas generator P_{GT} is equal to the power sold P_{sell}, the power of the electric chiller P_{EC} is equal to the power generated by the electric boiler P_{EB}, and the power generated at the load side P_{LOAD}, as shown below.

$$P_{PV} + P_{WT} + P_{buy} + P_{GT} = P_{sell} + P_{LOAD} + P_{EB} + P_{EC} \qquad (16)$$

Next is the thermal power balance, which needs to satisfy that the sum of the gas generator thermal power H_{GB}, and the electric boiler thermal power H_{EB} is equal to the load-side thermal power H_{LOAD}, as follows:

$$H_{GB} + H_{EB} * \eta_{\mathrm{EB}} = H_{LOAD} \qquad (17)$$

Finally, there is the cold power balance, which needs to be satisfied, as follows:

$$C_{EC} = C_{LOAD} \qquad (18)$$

The power balance is required for the IES to maintain stable operation, an important constraint.

2) Electrical energy storage constraints

The electrical energy storage is mainly displayed through the SOC of the battery, so the battery SOC needs to meet the following conditions.

$$\mathrm{SOC}_{min} \le SOC(t) \le SOC_{max} \qquad (19)$$

$$SOC_{zero} = SOC_{end} \qquad (20)$$

The SOC at each moment has to be below the maximum upper limit and below the minimum lower limit of the SOC value, and secondly the initial SOC has to be equal to the final SOC.

3) Thermal energy storage constraints

Thermal energy storage systems can significantly reduce system operating costs by optimizing energy management [27]. For an ideal thermal energy storage system, the constraints mainly include energy storage capacity constraints and charging and discharging thermal power constraints

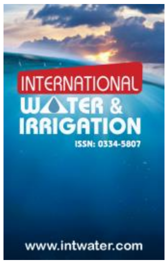
$$0 \le E(t) \le E_{max} \qquad (21)$$

$$0 \le P_{in} \le P_{cha\_max} \qquad (22)$$

$$0 \le P_{out} \le P_{discha\_max} \qquad (23)$$

Where $E(t)$ is the stored energy of the energy storage device at time t (unit: J or kWh), E_{max} is the maximum stored energy capacity of the energy storage device. P_{in} and P_{out} are the charging and discharging thermal power of the thermal energy storage system, P_{cha_max} and P_{discha_max} are the maximum charging and discharging constraints of the thermal energy storage, respectively.

4) Grid interaction power constraints



In the system, the IES can purchase power from the grid or sell excess power back to the grid. However, the power purchased, P_{buy}, and the power sold, P_{sell}, must be constrained by the transmission capacity of the grid. The power purchased and sold must satisfy the following constraints.

$$0 \le P_{buy} \le P_{buy\_max} \qquad (24)$$

$$0 \le P_{sell} \le P_{sell\_max} \qquad (25)$$

Where the P_{buy_max} and P_{sell_max} scores denote the maximum power allowed to be purchased and sold by the grid in that time period, respectively.

5) Equipment constraints

The equipment includes gas generators, gas boilers, electric boilers, and electric chillers, and the conditions to be met during operation are:

$$\begin{cases} 0 \le P_{GT}(t) \le P_{GT_{MAX}} \\ 0 \le H_{GB}(t) \le H_{GB_{MAX}} \\ 0 \le H_{EB}(t) \le H_{EB\_MAX} \\ 0 \le C_{EC}(t) \le C_{EC\_MAX} \end{cases} \qquad (26)$$

In the formula.， P_{GT_MAX}， H_{GB_MAX}， H_{EB_MAX}， C_{EC_MAX} represent the maximum power ratings of the equipment to which they belong, respectively.

6) Carbon Emission Constraints

(a) Constraints of multi-Region IESs

Carbon emissions in the entire system of multi-regional IESs come firstly from the part of power purchased by the IESs from the main grid and secondly from natural gas.

$$C_E(t) = \varepsilon^E \sum_t P_E(t) \qquad (27)$$

$$C_G(t) = \varepsilon^G \sum_t P_G(t) \qquad (28)$$

$C_E(t)$ is Carbon emissions from main grid, ε^E is share of carbon emissions from main grid, $P_E(t)$ is grid power at time node t; $C_G(t)$ is Carbon emissions from natural gas, ε^G is share of carbon emissions from natural gas, $P_G(t)$ is natural gas power at time node t

(b) Carbon emission constraints

$$C_{LE}(t) = e^E \sum_t P_E(t) \qquad (29)$$

$$C_{LG}(t) = e^G \sum_t P_G(t) \qquad (30)$$

$C_{LE}(t)$ is Carbon intensity of main grid, e^E is Carbon intensity of main grid; $C_{LG}(t)$ is Carbon production at time t, e^G is Carbon intensity of natural gas

4. Example analysis and results

4.1 Arithmetic setup

In this article, a multivariate IES composed of a single IES is taken as the research object, and MATLAB software is used for modelling, and the YALMIP toolbox and CPLEX solver in MATLAB are used to solve the model. Through this modelling method, the optimization analysis of the energy system can be carried out more accurately. In the modeling process, we used multiple sources of datasets for photovoltaic (PV) and wind turbines (WT), including three sets of predicted power generation data for PV power systems and wind turbines, which are used to simulate the power generation output of renewable energy sources. The PV and wind turbine prediction data used in the article are shown in Figure 3 below

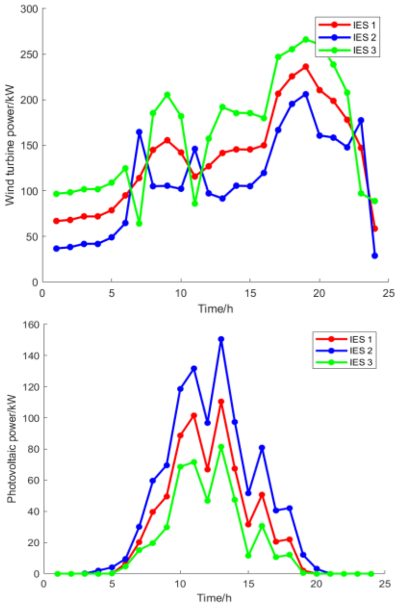


Figure 3: WT and PV power forecast data

Note: Load forecasting maps for PV and wind turbine generation

The WT power forecast data plot shows that the trend of wind power generation over the course of a day for IES 1, IES 2, and IES 3 shows significant regional differences. Notably, IES 3's wind power generation exhibits greater fluctuations at different times of the day, reaching peaks of around 250 kW at approximately 8 and 16 hours. This may be due to greater wind speed variability in the region where IES 3 is located. In contrast, IES 2's wind power generation is more stable, indicating that the wind resources in its region are more consistent. By analyzing these fluctuations, optimized scheduling can help different regions allocate power resources more effectively based on actual wind power generation, thereby improving system stability and energy efficiency [28]. The PV generation forecast data illustrates the changes in PV generation power for IES 1, IES 2, and IES 3 over time. Unlike wind power generation, PV generation power follows a typical sunlight pattern, with all regions reaching their peak PV power generation around noon (around 12 hours). IES 2's PV generation peaked at 150 kW, significantly higher than the other two regions. This suggests that IES 2 has better solar conditions or a larger PV panel area. The PV generation results also indicate that solar energy can be fully utilized during the day to reduce dependence on traditional energy sources, while multi-regional coordinated scheduling can effectively integrate other energy sources (such as WT or energy storage systems) to supplement power during periods of reduced sunlight.

The battery used in this article is a lithium battery, and the factors that externally affect the efficiency of the battery storage, including temperature, the degree of aging of the battery, etc., are uniformly set to an ideal state, and the specific parameters of the single battery used for battery storage are shown in Table.1. The thermal energy storage system used is based on the ideal material for thermal energy storage, and the ideal characteristics of the thermal energy storage material include low subcooling, low cost, easy availability, thermal stability, chemical stability, small volume change, non-toxicity [29], and high stability. stability, small volume change, non-toxicity, and low flammability, etc., and the specific parameters are assumed to be the same as those of the energy storage monobloc battery [30].

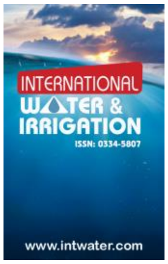


Table 1: Parameters of single battery

Parametric	**Number**
Rated Capacity	300
Initial Energy Storage Capacity	150
Charging efficiency	90%
Discharge efficiency	90%
Maximum Charging Power	160
Maximum Discharge Power	160

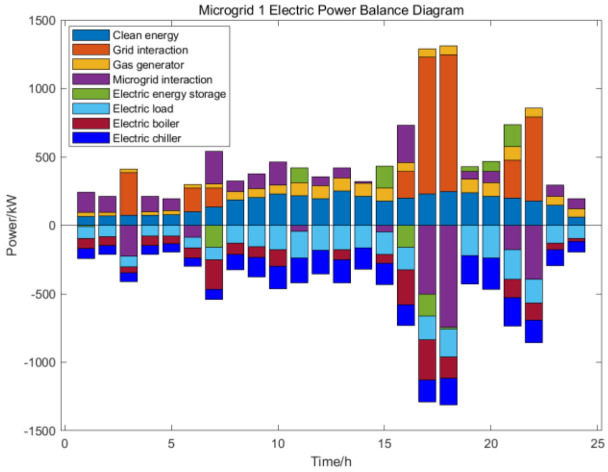
In addition, the system also covers the data of electric loads, heat loads and cold loads, which represent the energy demand of the system in different time periods. In order to achieve economic dispatch of the energy system, a set of hourly tariff data is also introduced into the model, as shown in Tab.2, which specifically includes the price of purchasing electricity and the price of selling electricity at each moment in time, and these tariff data are used to calculate the costs and revenues of the system when it purchases electricity from the grid or sells it to the grid at different time intervals.

Table 2: Time-of-use electricity price. [24]

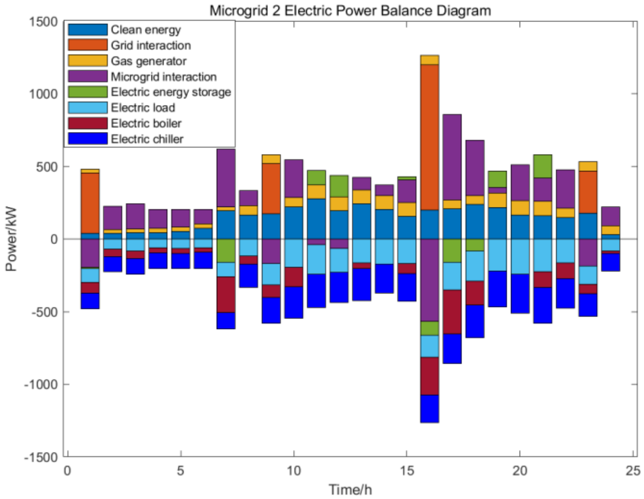
	TIME(h)	**PRICE(CNY)**
Peak period	12–14, 18–20	2.83
Normal period	8–11, 14–17, 21–23	1.67
Valley period	0-7	0.58

In the optimization process, the model not only needs to satisfy the power balance constraints of electricity, heat and cold loads, but also needs to comply with the operational limitations and constraints of each subsystem in the system. On this basis, the model solves the final energy system dispatch scheme by optimizing the objective function, including the specific values of the system's power purchase from the grid and power sale to the grid, as well as the corresponding power purchase cost, gas purchase cost and carbon emission cost.

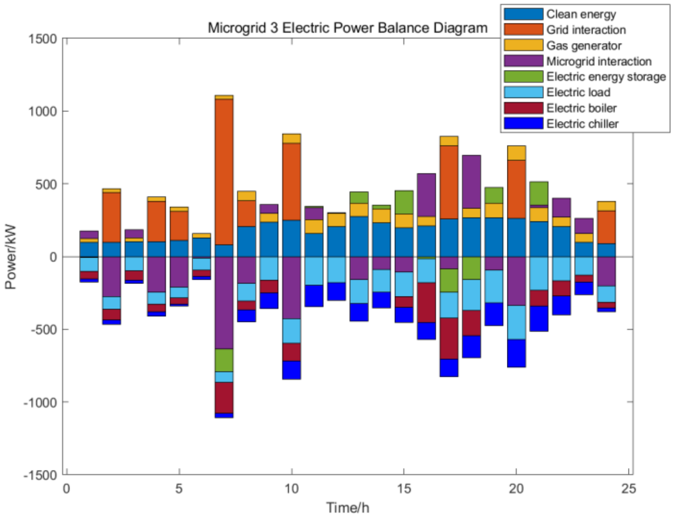
In particular, the electric power balance of the three single IES regions is shown in Figure 4, which demonstrates the details of the power supply and demand within each region;



(a)



(**b**)

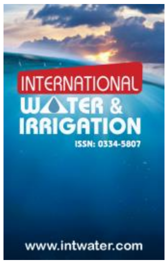


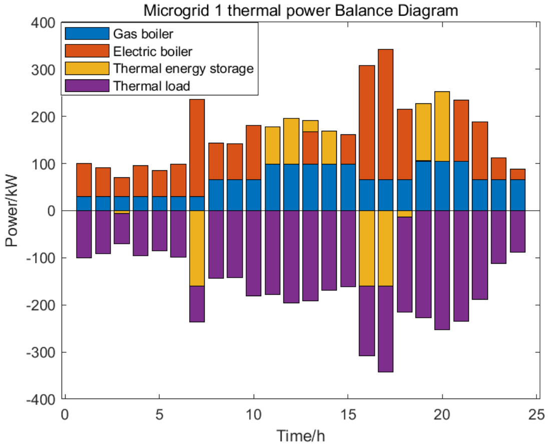
(c)

Figure 4: Electrical power balance of three single microgrids.

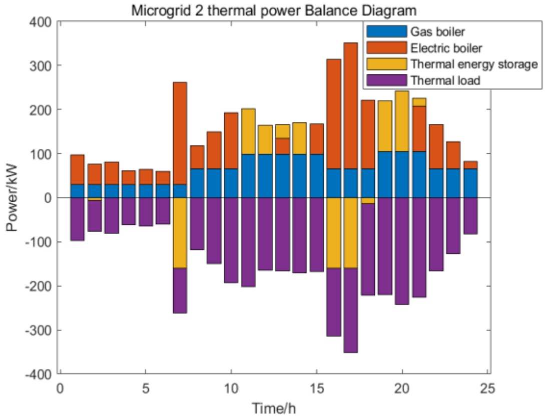
Note: (**a**)Microgrid 1 Electric power balance diagram. (**b**) Microgrid 2 Electric power balance diagram. (**c**) Microgrid 3 Electric power balance diagram.

The thermal power balance is shown in Figure 5, indicating the relationship between the heating equipment and the heat load in each zone;

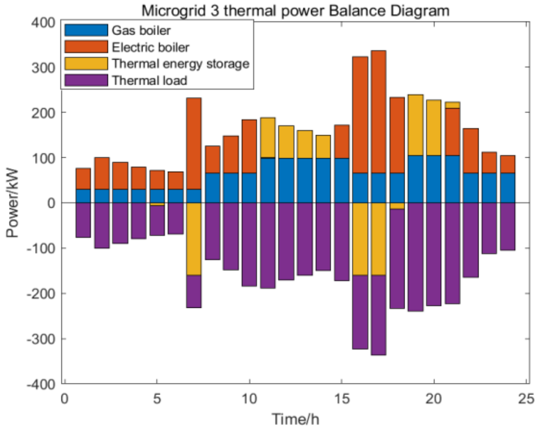




(a)



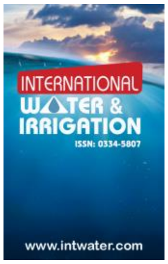
(b)



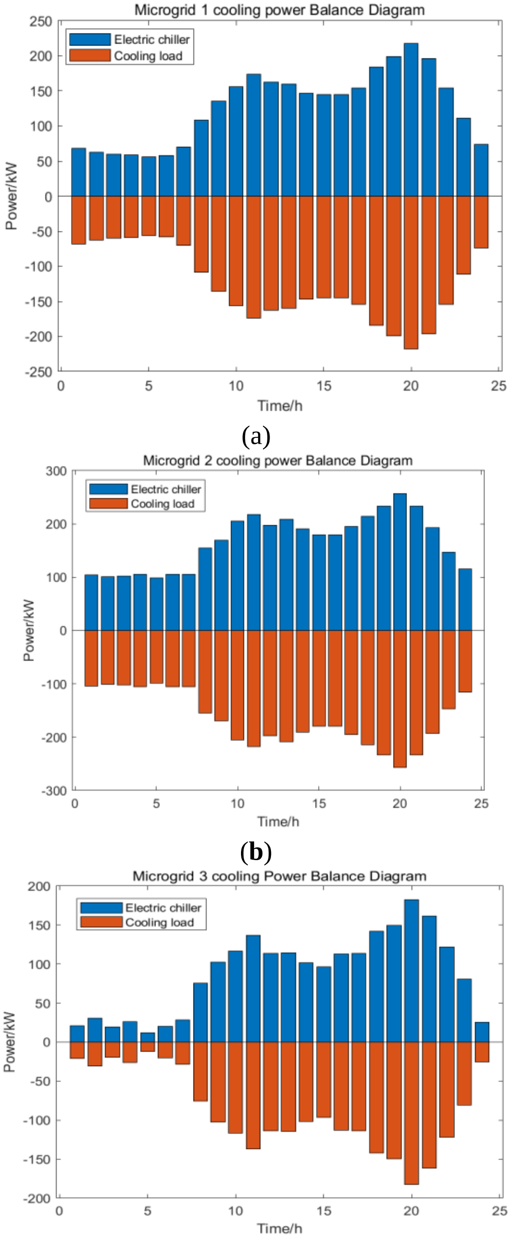
(c)

Figure 5: Thermal power balance of three single microgrids.

Note: (**a**)Microgrid 1 thermal power balance diagram. (**b**) Microgrid 2 thermal power balance diagram. (**c**) Microgrid 3 thermal power balance diagram.



Cold loads are also an important consideration, as they are supplied by electricity, so the stability of the power system may also be affected during periods of peak cooling demand [31]. The cooling power balance is shown in Figure 6, reflecting the matching of the load of the refrigeration equipment with the cooling demand in each area, and since there is only one type of equipment that generates the cooling load in this article, only the electric chiller and the cooling load constitute the power balance.

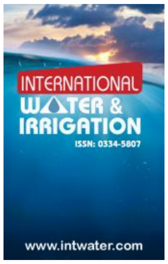


(a)

(b)

(c)

Figure 6: Cooling power balance diagram for three single microgrids.



Note: (**a**)Microgrid 1 cooling power balance diagram. (**b**) Microgrid 2 cooling power balance diagram. (**c**) Microgrid 3 cooling power balance diagram.

Ultimately, the article ensures that the IES is balanced in terms of power, heat and cooling demand through the comprehensive analysis of these data and constraints, and based on this, the total power purchase price of the system is calculated. Through this optimal scheduling, energy management optimization is achieved based on demand response, which can effectively reduce the operating costs of the system and improve the efficiency of energy use [32]

4.2 Example results

By calculating the total cost of the three single IESs, including the cost of electricity consumption, the cost of purchased gas and the cost of carbon emissions in them, and comparing them with the individual costs of the multifaceted IESs, the resulting data are shown in Table.3.

Table.3: Cost comparison of different methods

	Three single IES overlays	*Diversified IESs*
Cost of purchasing electricity (CNY)	2784.5177	2392.8702
Cost of Gas Purchase (CNY)	1990.9095	1822.711
Cost of carbon emissions (CNY)	804.075	712.3267
Total costs (CNY)	5579.5022	4927.9079

By comparison, it can be clearly seen that after the optimal scheduling of the multi-region IES, the Total costs and the costs of each part of the costs are significantly reduced, Total costs are reduced by the cost of electricity consumption is reduced by about 11.68%, Cost of purchasing electricity is reduced by 14.07%, Cost of Gas Purchase is reduced by about 8.45%, Cost of carbon emissions is reduced by about 11.4%, so it can be shown that after the scheduling optimization method proposed in this article, the cost is significantly reduced, especially the carbon emissions are also reduced more. The positive effect of energy sharing on reducing carbon emissions is highlighted in the literature [33] through a multi-objective optimization approach when coupling regional IES with renewable energy and energy storage. The application of this article kind of multidistrict IES can improve the energy utilization, save the system cost and reduce the carbon emission.

4.3 Impact of Carbon Emissions and Water Conservation on the System

Carbon emission control contributes to optimizing the economic efficiency of the system. By implementing carbon trading and reducing emissions, the system can lower carbon-related costs over long-term operations. This optimization allows the system to meet environmental regulatory requirements without additional economic burden and further saves costs through reasonable energy allocation.

Secondly, reducing carbon emissions significantly benefits the system’s environmental performance. The integrated energy system incorporates low- or zero-carbon energy sources, such as photovoltaic and wind power, reducing reliance on fossil fuels and thereby achieving significant greenhouse gas reductions. This not only helps mitigate global warming but also enhances the system's green image, aligning with the demands of sustainable development.

Lastly, carbon emission control enhances the system's flexibility and adaptability. With the application of energy storage technologies, the system can better respond to fluctuating load demands. By coordinating optimized scheduling between regions, the system ensures stable power supply while reducing emissions. This multi-regional collaborative scheduling approach not only improves the system's operational efficiency but also promotes the wider adoption of clean energy, creating a positive cycle that further strengthens the beneficial impacts of carbon emission control on the environment and economic performance of the system.

By finely managing water resource usage within multi-region IES, the system's impact on natural resources can be further minimized, achieving both energy and water conservation goals. For instance, water demand and water recycling parameters can be integrated into the optimization of various energy forms, such as electricity, cooling, and heating, thereby reducing dependence on new water sources. Additionally, in cooling and thermal storage processes, the application of efficient water recycling technology not only ensures system stability but also reduces water consumption, enhancing the overall sustainability of the system. This optimization method facilitates the achievement of green and environmental goals through the coordinated scheduling of water and energy, providing valuable insights for sustainable energy systems.

5. Conclusions

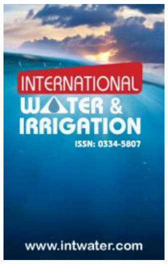
The article shows that the multi-region IES based on optimal dispatch has significant advantages in terms of environmental sustainability. Through collaborative scheduling between multiple regions and sharing of energy resources across regions, the system further optimizes the efficiency of energy utilization and reduces energy wastage. Energy storage technologies (e.g., battery storage and thermal storage) provide greater flexibility for IESs, enabling the system to maintain smooth operation during fluctuations in load demand [34]. Additionally, by effectively managing water resources and utilizing water efficiently in cooling and thermal cycles, the system can further reduce water consumption and enhance the environmental friendliness of the IES.

From a technical point of view, a single IES integrates multiple forms of energy supply such as photovoltaic, wind, and gas generators, and the article combines three individual IESs into a multi-region IES with distributed collaboration and scheduling optimization between the regions. In particular, through the refined management of the four loads of electricity, heat, cooling and gas, the system is able to realize the cross-regional deployment of energy in time and space, ensure the balance of energy supply and demand between different regions, and improve the operational efficiency of the overall energy system. The arithmetic results in this article show that the optimized multi-regional IES system has significant reductions in electricity and natural gas acquisition costs and carbon emissions: electricity costs are reduced by 11.68%, gas acquisition costs are reduced by 8.45%, and carbon emissions are reduced by 11.4%.

Thus, the integrated multi-regional energy system not only improves energy efficiency at the technical level, but also provides strong support for environmental protection and sustainable development by promoting the use of renewable energy sources and reducing carbon emissions. This optimization approach provides new ideas for the design and operation of future energy systems, and is an important reference value for promoting the green transition of global energy systems and maintaining environmental sustainability.

Data Sharing Agreement

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.



Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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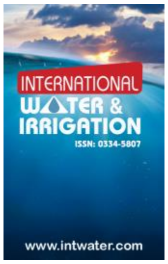

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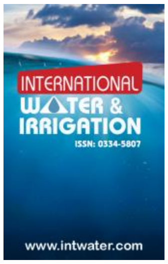

Appendix A.

Table A: Table of IES equipment and its parameters

Device name	*Parameter*	*Value*
Gas Generator	Number of units	1
	Power Generation Efficiency	0.3
	Heat production efficiency	0.7
	Rated power/kW	1000
Gas boilers	Number of units	1
	Heating efficiency	0.86
	Rated power/kW	1000
Electric Boiler	Number of units	4
	Heating efficiency	0.91
	Rated power/kW	250
Electric chillers	Number of units	2
	Refrigeration efficiency	0.95
	Rated power/kW	500