Journal of Global Information Management
Volume 31 • Issue 1

Impact of Carbon Capture (Storage) and Carbon Tax on Economic Dispatch of an Integrated Energy System

Zhizhou Tan, School of Management, China Institute for Studies in Energy Policy, Xiamen University, China
Boqiang Lin, School of Management, China Institute for Studies in Energy Policy, Xiamen University, China*
https://orcid.org/0000-0002-1308-400X

ABSTRACT

Finding the balance between economy and low emission of an integrated energy system (IES) has become one of the current research hotspots. This article introduces the carbon tax and carbon capture (storage) technology within the framework of the IES model. The IES comprises of components such as combined heat and power units equipped with carbon capture facilities, wind power generators, photovoltaic panels, and energy storage systems. The objective function of the model is the minimization of operational costs. Low-carbon economic operation dispatching problem under the constraints of energy conversion, energy balance, and operation cost is studied based on a mix-integer linear programming model. Through sensitivity analysis, this study explores the impact of varying carbon tax levels on the operational costs and emissions of an IES while considering peak and valley price differences. The emission reduction potential of the IES under different policy and technology scenarios is also estimated.

KEYWORDS

Carbon Capture And Storage, Carbon Tax, Dispatch Optimization, Emission Reduction Potential, Low Carbon Dispatch, Mixed-Integer Linear Programming, Operating Expenses, Renewable Energy

1 INTRODUCTION

With carbon neutrality targets and the process of global climate governance, the energy sector is undergoing a greener transformation (Lin & Ma, 2022). Global electricity demand has grown by at least 70% in the last 20 years, and this figure is estimated to increase to 170% by 2040 (Wesseh & Lin, 2022). Since the current energy mix still has a high proportion of fossil fuels, fossil energy consumption for power generation purposes is of particular concern. The power sector is responsible for roughly 40% of the total carbon emissions generated by the global energy sector (Jin, Zhou, Li, Bai, & Wen, 2020). Therefore, the general view is that active carbon emission management in the

DOI: 10.4018/JGIM.331695

*Corresponding Author

power energy sector will play an important role in addressing environmental change and promoting the development of a green transformation of the power industry(Cui, Li, Song, & Zhu, 2019; González-Carrasco, Robina-Ramírez, Gibaja-Romero, & Sánchez, 2023).

Optimal environmental and economic dispatch is a fundamental issue in managing energy systems that cannot be ignored. Energy systems' environmental and economic dispatch aims to meet growing energy demands while minimizing total operating costs and emissions to achieve urgent emission reduction targets (Zhu, Ren, Habibi, Mohammed, & Khadimallah, 2022). Driven by various factors such as energy security, carbon peaking, and carbon-neutral targets, renewable energy sources are becoming a larger part of the energy mix, with their proportion increasing and installed capacity expanding rapidly(Y. Zhang, Zhang, & Ng, 2021). Despite their advantages, external environmental factors can affect wind and photovoltaic power generation, leading to instability in their output. As a result, other types of energy are needed to achieve a dynamic balance with the demand load in real-time, which invariably increases IES operation costs. To address the challenges posed by the increasing penetration of wind and PV power into the grid, expenditures on peak regulation, frequency modulation, and energy storage are likely to increase significantly. The challenge of increased operating costs could become a potential barrier to the clean development of future energy systems (Yao, Fan, Zhao, & Ma, 2022).

Integrating carbon capture and storage (CCS) technologies into energy systems coupled with conventional fossil energy power plants has the potential to reduce energy system emissions significantly. CCS is recognized as a crucial strategy in addressing climate change while accelerating the clean transition of energy systems. Major technological advances regarding CCS include pre-combustion capture, post-combustion capture, and oxygen-enriched combustion capture(Z. Tan, Zeng, & Lin, 2023). Post-combustion capture is the process of capturing CO_2 after the fuel has been combusted, primarily by extracting CO_2 from the flue gas through chemical solvents. Post-combustion capture is currently the most mature technology and has the most potential for commercial application(Gustafsson, Sadegh-Vaziri, Grönkvist, Levihn, & Sundberg, 2021). Once CO_2 is captured, it needs to be compressed and transported by pipeline or other means of transportation to a dedicated location for permanent storage. Carbon storage technologies consist of four main approaches: geological storage (injection into the geological formation), mineral carbonation storage (reaction with minerals to form stable carbonates), terrestrial storage (absorption by biological photosynthesis), and ocean storage (injection into the deep ocean) (Kim, Kim, Kang, & Park, 2016; Zhao et al., 2023).

As an emerging technology with high emission reduction potential, CCS can provide a new option to dispose of conventional fossil energy generation units in the current energy system(Lin & Tan, 2021). For example, CCS retrofitting instead of directly decommissioning or dismantling coal-fired power plants to retain its role as a backup power source in the energy system. This option may enable the energy system to maintain supply stability during the transition process and facilitate the energy system to reach a higher level of renewable energy consumption. Although the addition of CCS technology is expected to reduce emissions from conventional power plants effectively, the corresponding investment in retrofitting will also result in higher expenditure (L. Yang et al., 2021). To achieve a high level of renewable energy consumption and stable power supply in the energy transition process, it is imperative to investigate the synergy and optimal dispatch of different power sources in the energy system. In addition, finding a balance between carbon emission reduction and economical operation in the energy system transition process also needs further investigation.

The development of clean energy systems and energy policies worldwide will emphasize the importance of balancing the security of supply, economic cost, and energy conservation(Du, Zheng, & Lin, 2022). Efficiently integrating a substantial amount of clean energy into the current energy system and enhancing energy supply stability and cost-effectiveness is a pressing challenge facing China and other nations in their endeavors to advance clean energy systems in the future. As a result, the concerns of future energy policy will probably focus on optimal dispatch and carbon emission control (J. Li & Ho, 2022).

The carbon tax is a taxation system on CO_2 emissions from economic activities, with the main aim of reducing emissions to protect the environment and slow down the global warming trend. Carbon tax policies vary from country to country, with some countries taxing only businesses while others levy carbon taxes on households and businesses. Several countries around the world have taken steps to implement carbon taxes and have achieved positive results(H. Wang & Wang, 2022). By 2020, 27 countries or regions have implemented carbon taxes worldwide(Carroll & Stevens, 2021). Among them, Finland may be the first country in the world to impose a carbon tax on households and businesses (Jia, Lin, & Liu, 2023). In addition, there are differences in carbon tax rates between countries. Uruguay may have the highest carbon tax rate, paying \$137 per ton of CO_2 emissions as of 2022, while Poland may have a carbon tax rate of less than \$1 per ton (Bank, 2022).

CCS is a technology with great potential to reduce emissions, and conventional thermal power units retrofitted with CCS will play a key role in complementing and balancing the instability of wind and PV power generation in an IES. Market-oriented carbon emission control policies have effectively reduced emissions over the past decades of practice(Lin & Tan, 2023). However, the role of carbon tax in the future climate governance framework and its impact on the IES needs to be further assessed. In general, there are few studies on integrating and configuring CCS, renewable energy, and energy storage devices in the IES and investigating their optimal management and dispatch under the carbon tax regime. In addition, most of the research on the issue of CCS and carbon tax focuses on examining the macro up-bottom issues, while the analysis of the joint impacts of these two elements on the micro IES level is still insufficient. Therefore, this study focuses on the following questions: what will be the impact of CCS technology on the economic dispatch management and emission reduction potential of IES? What will be the impact of the carbon tax on the future dispatch, operation mode, and operation cost of the IES? And how should the carbon tax policy be designed and dynamically evaluated during the policy planning process?

The objective of this research is to investigate the effects of CCS as a sustainable development technology and carbon tax as an emission reduction policy on the IES under the context of carbon neutrality. The technical information of CCS and other sustainable facilitates, output information of renewable energy, and demand load information are comprehensively synthesized to study the scheduling management and operational performance of the IES. This study adopts a typical IES to construct a mixed-integer linear programming (MILP) model. The model examines a combined heat and power (CHP) unit, energy storage facilities, and time-of-use pricing to seek an efficient dispatch model with the lowest operating cost. On the supply side of the model, different types of power supply are simulated at the hourly level. The economic optimization problem of minimizing the operating cost under various constraints is also examined.

The structure of this paper is as follows: Chapter 2 provides a comprehensive review of the current literature on the optimal dispatch of IES; Chapter 3 describes the optimized dispatch model presented by this study; Chapter 4 discusses and analyzes the results of the optimal dispatching simulations; and in Chapter 5 a summary of the main findings and policy implications is concluded.

2 LITERATURE REVIEW

Different papers examine CCS technology's emission reduction potential and economic cost implications in different theoretical frameworks (K. Li, Yang, & Wei, 2023; S. Liu et al., 2023; X. Wang, Tang, Meng, & Su, 2023). Considering the production characteristics and CO_2 emission reduction constraints of different units in an IES, a MILP model enjoys a special advantage in finding practical solutions to low-carbon power economic dispatch optimization problems (AlHajri, Ahmadian, & Elkamel, 2021; Yamchi, Safari, & Guerrero, 2021). As a potentially effective emission reduction policy, carbon taxes have been gradually implemented in several countries worldwide (Tarufelli, Snyder, & Dismukes, 2021). Considering the addition of CCS technology and carbon tax policy, the economically optimal dispatch of integrated energy systems may exhibit new features. Several scholars have paid attention to the problems and challenges that climate governance and energy transition may bring to the economic dispatch of integrated energy systems, as many corresponding research works have been conducted.

The problem of optimal dispatch in power systems, considering uncertainties in wind power output and the need to balance environmental and economic concerns, was examined by Jin, Zhou, Zhou, and Miao (2014). This paper proposed a multi-objective stochastic programming model considering both conventional and wind turbines, which provides a solution for different economic, environmental, and wind power development levels. A multi-objective stochastic planning model that considers both conventional generators and wind turbines is also proposed, providing suggestions for finding a balanced power dispatch model. Zhu et al. (2022) proposed a novel Swarm-based metaheuristic to solve the multi-objective optimization problem of energy systems from an environmental-economic perspective. The proposed algorithm's superiority in evaluation metrics and convergence rate is confirmed through comparisons with other optimization algorithms. Wesseh and Lin (2022) proposed an electricity market model considering time-of-use pricing to examine the impact of power plants, electric vehicles, energy storage, and other energy sources on an IES. Their study showed the interplay between power plants, electric vehicles, energy storage devices, and electricity prices. This study shows that the ramping parameters of different power technologies and the optimal utilization of EV battery capacity are the key factors to be considered when designing a time-of-use pricing mechanism to enhance the efficiency and stability of grid operation.

Regarding economic and environment-friendly optimal dispatching of IES, reducing the operating costs and overall emissions of IES through optimal dispatch is a major focus of current research (Ding, Tan, Shan, Han, & Zhang, 2023; Jin, Zhou, Li, Guo, & Zhang, 2019; Z.-F. Liu et al., 2021). Some research approaches include mixed-integer programming and genetic algorithms aiming to achieve these objectives by finding optimal dispatching schemes. The reliability and security of integrated energy systems are other key topics of current research. Integrated energy systems usually consist of a combination of several energy varieties. The combination of different energy technologies can reduce the reliance on a single energy technology to some extent and improve the reliability and security of the whole system (Mansourshoar, Yazdankhah, Vatanpour, & Mohammadi-Ivatloo, 2022). In addition, researchers have also conducted research on how to deal with various contingencies and failure situations, e.g., extreme weather (Xie, Sun, Fu, Chen, & Bie, 2023), sudden changes in supply and demand (Su et al., 2020), and troubleshooting (Cao et al., 2022). Some common approaches include designing systems to be fault tolerant, establishing emergency backup mechanisms, and creating distributed energy systems.

Many other scholars have conducted research work in terms of policy and regulatory impact assessment on IES. It is imperative to provide appropriate policy guidance to enhance energy efficiency and mitigate carbon emissions resulting from energy generation(C. Xu et al., 2023). The impact of renewable energy portfolio standards (Q. Tan, Ding, Zheng, Dai, & Zhang, 2021), carbon trading mechanism (R. Wang, Wen, Wang, Fu, & Zhang, 2022), green certificate system (X. Zhang, Guo, & Zhang, 2023), and time-of-use pricing (S. Yang et al., 2020) and other related policies on the IES are discussed and analyzed, providing the important theoretical basis for the formulation of policies and regulations, and promoting the sustainable development of the IES.

The flexibility and scalability of IES are important characteristics of future energy systems(Pappas et al., 2023). With the development of new energy technologies and the increasing proportion of renewable energy in the energy system, the volatility of power output is expected to increase, placing greater demands on the rapid response, peak and frequency regulation capabilities, and other energy technologies in the system. As the energy transition process continues to advance and the energy demand continues to grow, the expansion and transformation of the energy system are also essential. For example, expanding the power grid's capacity may be necessary to satisfy the requirement for renewable energy consumption. The mismatch between peak and valley demand load and renewable energy output is a major factor contributing to the challenges of consuming renewable energy and rising operational costs in the energy system. Setting peak and valley energy prices with a certain price difference and installing additional energy storage facilities is a feasible way to promote peak and valley reduction of demand-side load, which is expected to reduce the additional installed investment cost to meet peak hour load and also provide more flexibility for integrated energy optimization and dispatch (Guo, Ye, & Zhao, 2022; Lyu et al., 2023).

In the current situation where the scale of extra-high voltage grid and energy storage is insufficient to support the large-scale consumption of renewable energy fully, the flexibility retrofit and CCS retrofit of traditional fossil energy generating units become a potential option worth considering. Few studies have examined both emerging carbon capture technology and carbon tax policies. Their impact on the economic dispatch of integrated energy systems has not been fully explored in a way that could be critical and enlightening for future integrated energy systems' construction and operation management. CCS technology can effectively reduce carbon emissions from conventional fossil energy generation while retaining its stable output characteristics, which is expected to provide more peaking and frequency adjustment options for integrated energy systems. This paper proposes an IES simulation model incorporating CCS and carbon tax policy into the analytical framework. By examining different policy and technology combinations, the model can identify optimal dispatch strategies for IES that improve the economic and environmental performance of the overall system.

This study provides several marginal contributions: (i) a novel IES simulation model is developed, including the carbon capture and storage module. The problem of low-carbon economic operation dispatch is explored by considering the constraints of energy balance, energy conversion, and operation cost. (ii) The impact of the carbon tax mechanism on the operation of IES is investigated, considering the price difference between peak and valley, typical wind power output, and thermal/electric load. Scenarios are set up to explore the emission reduction potential of the IES under different policy and technology settings. (iii) Based on the findings, quantitative and qualitative recommendations are made for policymakers and IES managers to facilitate the formulation of relevant policies. The findings of this study are expected to enrich the existing research and to shed light on the construction and operational management of future IESs.

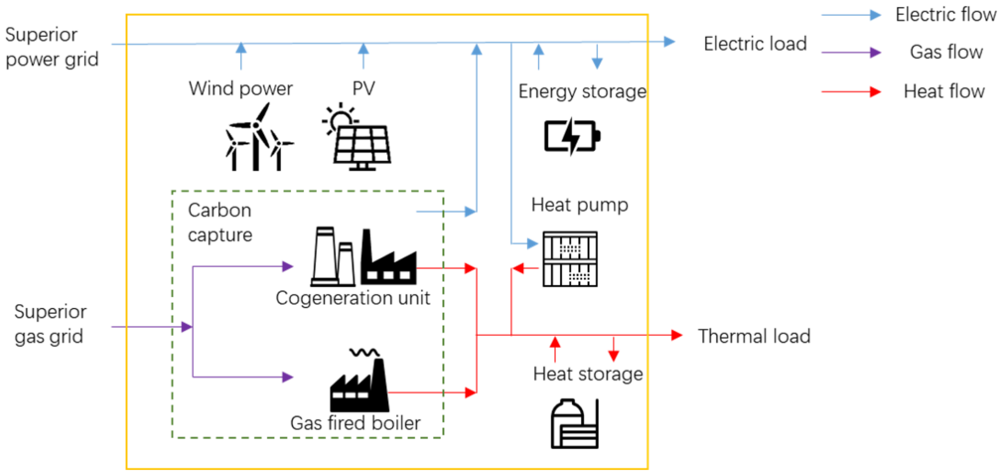
3 METHODOLOGY

3.1 IES Modeling Framework and System Boundary

As shown in Figure 1, the system boundary of the IES model presented by this paper encompasses renewable energy sources like photovoltaic and wind power and conventional energy units such as CHP. Additionally, the model incorporates electricity storage, heat storage, and a heat pump (HP) to meet the end-use electricity and heat loads in line with the output of the renewable energy units. Building on the work of Zhenbo WEI et al. (2022), this paper proposes an optimal economic dispatch model for the IES, which considers both carbon tax policy and carbon capture and storage technology. Common CCS retrofit technologies include post-combustion, pre-combustion, and oxygen-enriched combustion, of which post-combustion capture is the most promising for commercial application (Cau, Tola, Ferrara, Porcu, & Pettinau, 2018). The CCS retrofitting to be considered in this study also belongs to this category. The captured CO_2 is transported to a suitable storage site, usually a well-confined geological encirclement or deep ocean (Zhao et al., 2023). In this study, the storage options for CO_2 are transported by pipeline and injected into the geological stratum.

The MILP plays a vital role in the field of combinatorial optimization research, finding applications in diverse areas such as logistics, power dispatching, and production scheduling. Derived from the MIP problem, the MILP distinguishes itself by allowing integer and continuous variables in the optimization model, while MIP focuses solely on linear forms within the objective function. The MILP's objective function and model boundary conditions are commonly expressed through a linear combination of variables (Finkenrath, Faber, Behrens, & Leiprecht, 2022). Constructing an IES simulation model and formulating the IES dispatch optimization as a MILP problem makes it

Figure 1. IES model boundary diagram



possible to find an optimal mathematical solution, facilitating informed decision-making in practical applications (J. Zhang et al., 2023).

3.2 System Economic Optimization Dispatch Model

3.2.1 Objective Function

The objective function of the optimal dispatch for the proposed IES in this study aims to improve energy system operation efficiency and reduce overall emissions:

$$\min C = \pi_{CO_2}\sum_{t=1}^{T} Q_{CO_2,t} + \sum_{t=1}^{T}\sum_{i=1}^{N}\pi_i OM_{i,t} + \sum_{t=1}^{T} P_{e,t}Q_{e,t} + \sum_{t=1}^{T} P_{g,t}Q_{g,t} \tag{1}$$

Where, $Q_{CO_2,t}$ denotes the carbon emission of the IES at time t, $OM_{i,t}$ denotes the output of facilities i at time t, π_i denotes the operation and maintenance(O&M) factor of equipment i, $Q_{e,t}$ denotes electricity purchased from the superior grid at time t, $Q_{g,t}$ denotes gas consumption at time t, $P_{e,t}$ and $P_{g,t}$ are respectively the electricity and gas prices at time t.

3.2.2 Constraint Functions

3.2.2.1 Constraints of Energy Balance

The output of the heating units in the system should be balanced with the heat demand in real-time:

$$\sum_{i=1}^{N} H_{i,t} - H_{sch,t} + H_{sdis,t} = H_{l,t} \tag{2}$$

Where, $H_{i,t}$ denotes the amount of heat generated by the ith heating unit at time t, $H_{sdis,t}$ denotes the amount of heat discharged by the thermal storage facility at time t, $H_{sch,t}$ denotes the heat charge of the thermal storage facility at time t, and $H_{l,t}$ denotes the heat demand load at time t.

Similarly, to accommodate the electricity demand, the power supply in the system should be balanced with the real-time power demand:

$$E_{b,t} + \sum_{i=1}^{N} E_{i,t} - E_{sch,t} + E_{sdis,t} = E_{l,t} \tag{3}$$

Where, $E_{i,t}$ denotes the amount of electricity generated by the ith generation unit at time t, $E_{sdis,t}$ denotes the discharge capacity at time t of the electric storage, $E_{sch,t}$ denotes the charging capacity at time t of the electric storage, $E_{l,t}$ denotes the demand load of electricity at time t, $E_{b,t}$ denotes the electricity purchased from the superior power grid.

3.2.2.2 Restrictions on the Output of Wind and Photovoltaic Power

The constraint of electricity generated by wind power could be represented by:

$$0 \le E_{W,t} \le E_{Wf,t} \tag{4}$$

The photovoltaic output constraints be expressed as:

$$0 \le E_{PV,t} \le E_{PVf,t} \tag{5}$$

Where, $E_{W,t}$ and $E_{PV,t}$ denote the true output of wind power and PV at time point t respectively, $E_{Wf,t}$ and $E_{PVf,t}$ denote the projected output respectively for wind and PV power at time point t.

3.2.2.3 Electrical Energy Storage (EES) Constraints

According to Zhenbo; WEI, REN, and HUANG (2020) the constraints associated with EES can be expressed as:

$$\delta_{sch,t} + \delta_{sdis,t} \le 1 \tag{6}$$
$$\delta_{sch,t} E_{sch,t}^{\min} \le E_{sch,t} \le \delta_{sch,t} E_{sch,t}^{\max} \tag{7}$$
$$\delta_{sdis,t} E_{sdis,t}^{\min} \le E_{sdis,t} \le \delta_{sdis,t} E_{sdis,t}^{\max} \tag{8}$$

The energy storage charge/discharge rate constraint could be represented by:

$$E_{s,t} - E_{s,t-1} = \eta_{sch} E_{sch,t} - \eta_{sdis} E_{sdis,t} \tag{9}$$

The energy storage capacity constraint could be represented by:

$$E_{s}^{\min} \le E_{s,t} \le E_{s}^{\max} \tag{10}$$

Where, $\delta_{sch,t}$ and $\delta_{sdis,t}$ are the logical variables indicating the state of charge and discharge of electrical power storage facility; $E_{sch,t}^{\min}$ and $E_{sdis,t}^{\min}$ denote the electrical energy storage facility minimum charge/discharge power; $E_{sch,t}^{\max}$ and $E_{sdis,t}^{\max}$ denote the electrical energy storage facility maximum charge/discharge power; $E_{s,t}$ denotes the storage capacity of the electrical energy storage facility at time t; η_{sch} and η_{sdis} denote electrical energy storage facility charge and discharge efficiency; $E_{s}^{\min}$ and $E_{s}^{\max}$ indicate the smallest and biggest storage capacity of the EES facility.

3.2.2.4 CHP Unit Output Constraints

$$0 \le E_{CHP,t} \le E_{CHP,\max} \tag{11}$$

$$E_{CHP,t} = E_{GT,t} + E_{ORC,t} \tag{12}$$

$$H_{CHP,t} = \sigma_t \eta_{WHB} H_{GT,t} \tag{13}$$

$$E_{GT,t} = \eta_{CCS} \eta_{EGT} \phi_g Q_{CHPg,t} \tag{14}$$

$$H_{GT,t} = \eta_{HGT} \phi_g Q_{CHPg,t} \tag{15}$$

$$E_{ORC,t} = (1-\sigma_t) \eta_{ORC} H_{GT,t} \tag{16}$$

Where, $E_{CHP,t}$ denotes CHP's actual electricity production at time point t, which consists of gas turbine and waste heat recovery power generation; $E_{CHP,\max}$ denotes a CHP unit's maximum electricity generation capacity; σ_t denotes the proportion of thermal allocated to the waste heat recovery boiler(WHB) at time t, η_{WHB} and η_{ORC} are the energy conversion efficiency factors of WHB and waste heat power generation(WHP) unit, respectively; $E_{GT,t}$ and $H_{GT,t}$ denote the gas turbine's power yield and heat yield at time point t, η_{EGT} and η_{HGT} denote the efficiency coefficient of power generation and the efficiency coefficient of heat generation of the gas turbine respectively; ϕ_g denotes the natural gas heat value, $Q_{CHPg,t}$ denotes the amount of gas consumed by the CHP at time point t, and $E_{ORC,t}$ denotes the electricity production of WHP generation unit at time t.

CCS retrofitting of IES may result in a loss of unit output efficiency. CCS technology is a key approach to reducing greenhouse gas emissions but it does not come without a cost. Loss of system efficiency is one of the major problems faced in the carbon capture process. Both the compressor and the solvent regeneration in the CO_2 capture process consume large amounts of energy (Kotagodahetti, Hewage, Karunathilake, & Sadiq, 2022). This causes the power plant or energy system to suffer a loss of efficiency which can be presented by η_{CCS}.

3.2.2.5 Heating Constraints

For the IES, the heat demand is mainly covered by the combination of gas boiler and heat pump (Z. XU, SUN, XIE, WANG, & ZHONG, 2020):

$$H_{GB,t} = \eta_{HGB} \phi_g Q_{GBg,t} \tag{17}$$

$$0 \le H_{GB,t} \le H_{GB,\max} \tag{18}$$

$$H_{HP,t} = \eta_{HP} E_{HP,t} \tag{19}$$

$$0 \le H_{HP,t} \le H_{HP,\max} \tag{20}$$

Where, $H_{GB,t}$ denotes the heat production from the gas boiler at time point t, η_{HGB} denotes the coefficient of heat production efficiency of the gas boiler, $Q_{GBg,t}$ denotes the gas boiler's gas consumption at time point t, and $H_{GB,\max}$ denotes the gas boiler's rated maximum heat output power; $H_{HP,t}$ denotes heat pump's thermal output at time point t, η_{HP} denotes the heat pump's coefficient of performance, $E_{HP,t}$ denotes the heat pump's power consumption at time point t, and $H_{HP,\max}$ denotes the heat pump's maximum output power, $Q_{CHPg,t}$ denotes the gas consumed by the CHP at time point t.

3.2.2.6 Thermal Energy Storage (TES) Facility Constraints

$$\kappa_{sch,t} + \kappa_{sdis,t} \le 1 \tag{21}$$

$$\kappa_{sch,t} H^{\min}_{sch,t} \le H_{sch,t} \le \kappa_{sch,t} H^{\max}_{sch,t} \tag{22}$$

$$\kappa_{sdis,t} H^{\min}_{sdis,t} \le H_{sdis,t} \le \kappa_{sdis,t} H^{\max}_{sdis,t} \tag{23}$$

The thermal energy storage charging and discharging rate constraint could be represented by:

$$H_{s,t} - H_{s,t-1} = \theta_{sch} H_{sch,t} - \theta_{sdis} H_{sdis,t} \tag{24}$$

The capacity constraint of thermal storage facility could be represented by:

$$H^{\min}_{s} \le H_{s,t} \le H^{\max}_{s} \tag{25}$$

Where, $\kappa_{sch,t}$ and $\kappa_{sdis,t}$ are the logical variables indicating the state of charge and discharge of thermal storage facility, $H^{\min}_{sch,t}$ and $H^{\min}_{sdis,t}$ denote the thermal storage facility minimum charge/discharge power, $H^{\max}_{sch,t}$ and $H^{\max}_{sdis,t}$ denote the thermal storage facility maximum charge/discharge power, and $H_{s,t}$ denotes the storage capacity of the thermal storage facility at time t; θ_{sch} and θ_{sdis} denote thermal storage facility charge and discharge efficiency, $H^{\min}_{s}$ and $H^{\max}_{s}$ indicate the smallest and biggest storage capacity of the TES facility.

3.2.2.7 Ramping Constraint

According to Yu, Chu, Sun, and Liu (2022), the ramping constraint of the unit can be expressed as

$$r_{i,d} T \le E_{i,t} - E_{i,t-1} \le r_{i,u} T \tag{26}$$

Where, $r_{i,d}$ and $r_{i,u}$ denote the downside and upside ramping rates of the unit, respectively; T denotes the unit time of 1 hour.

3.2.3 The Amount of Carbon Captured

In the IES proposed by this study, the gas boiler and the gas turbine are the main sources of CO_2 emission. The CO_2 emissions in the system at moment t could be represented by:

$$Q_{CO_2,t} = f_e \cdot f_c \cdot (\varepsilon \cdot E_{GT,t} + H_{GT,t} + H_{GB,t}) \tag{27}$$

Where, f_e denotes the unit's CO_2 emission coefficient, f_c denotes the CO_2 capture efficiency of the CCS facility, ε is the power conversion factor.

3.3 The Algorithm of Model Solution

The IES optimal dispatch model considering carbon tax and CCS proposed by this paper can be considered as a MILP model. To solve this type of optimal programming problem, commercial software such as CPLEX, GAMS, and LINGO is typically used (He et al., 2018; Huang, Wang, & Liu, 2022; Ma, Yi, & Fan, 2022; Q. Tan, Mei, Ye, Ding, & Zhang, 2019). In this paper, code for the optimization model was written based on the Yalmip toolkit in Matlab, and the CPLEX optimization software was invoked to solve the optimal dispatch problem for the IES model. Detailed solution procedures can be found below:

Step 1: build operation model of CHP unit, gas boilers, electric/thermal energy storage, heat pumps, and other devices;

Step 2: introduce the peak valley energy price and carbon tax mechanism, and build the objective function with the sum of energy purchase cost, carbon tax cost, and O&M cost;

Step 3: The objective function is solved under multiple constraints by calling the CPLEX software using the Matlab platform Yalmip toolkit.

3.4 Parameter Collection and Scenario Setting

Table 1 shows the basic parameters of the IES to be simulated in this study. Figure 2 shows a typical electricity and heat load demand curve, time-of-day electricity, and thermal prices. Typical wind and PV, output prediction curves, are illustrated in Figure 3. The optimal dispatch analysis is performed with a simulation period of 24 hours and a simulation step of 1 hour. The cost per ton of CO_2 captured is set at 600 RMB/ton of CO_2 for CHP unit retrofits with CCS (Cai, Li, & Zhang, 2021), and the cost of transportation and storage cost of CO_2 is 100 RMB/ton and 50 RMB/ton, respectively (L. Yang, Xu, Yang, Fan, & Zhang, 2019).

Figure 2. Typical load forecasting and time-of-use prices for IES

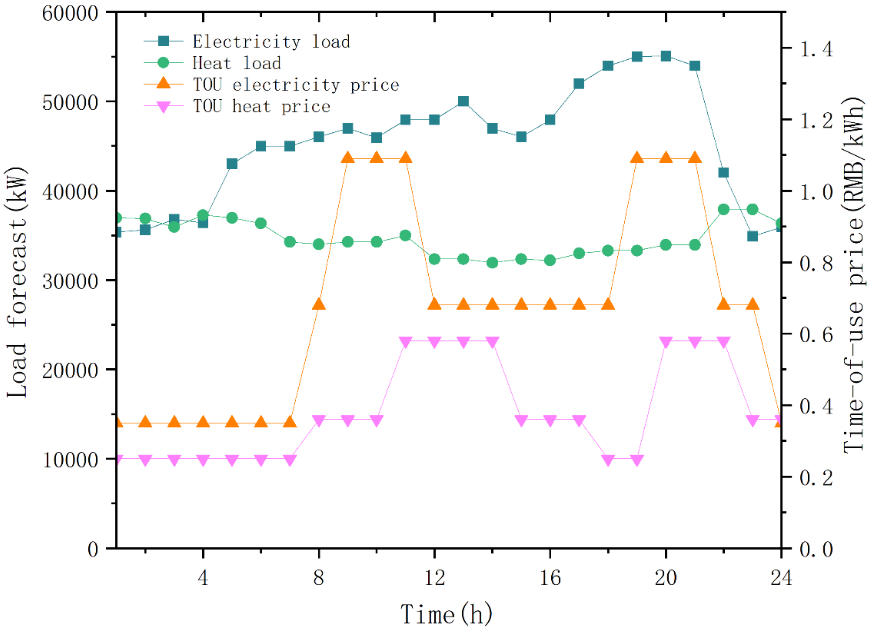
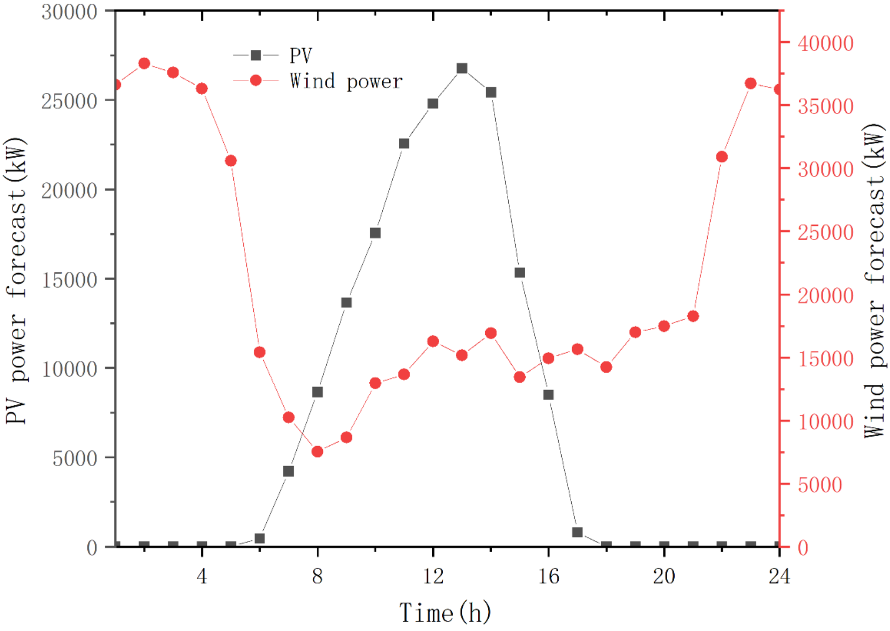


Figure 3. Typical forecasted output of wind and photovoltaic power



As shown in Table 2, four operational scenarios are set up to analyze the influence of carbon tax and CCS retrofit on the optimal economic dispatch of the IES. Scenario 1 considers the impact of the carbon tax policy alone. Scenario 2 separately examines the impact of CCS retrofit on the optimal dispatch of the IES. In Scenario 3, carbon tax policy and CCS retrofit are considered simultaneously. Scenario 4 is used as a control group, as both carbon tax and CCS retrofit are ignored. The economic and emission performance of the IES optimal dispatch model under the four scenarios will be shown in the next section.

4 MAIN RESULTS AND SENSITIVITY ANALYSIS

4.1 Analysis of the Results of Scenario Setting

Figure 4 presents the simulation results of hourly IES dispatch management optimization for four scenarios, including the power load balance of the IES and the output of each device. The nighttime corresponds to the peak wind power output period, during which the average cost of wind power generation is relatively low. Prioritizing the utilization of wind energy helps to reduce the overall operational costs of the IES. Therefore, during the period from 22:00 to 5:00, the electricity demand is mainly supplied by wind energy, with a small amount of electricity deficit met through power purchases from the higher-level grid. The period from 0:00 to 04:00 represents a valley electricity consumption period, characterized by lower electricity demand and electricity price. There is surplus electricity available during this time, which can be stored in batteries for later use.

Power demand enters the peak hour at 7:00-11:00, and PV power generation output starts to climb gradually. During the period from 9:00 to 11:00, time-of-use electricity price is at its peak. Compared to purchasing power from the higher-level grid, it is more cost-effective to utilize the CHP unit in conjunction with wind and photovoltaic power generation, as well as energy storage discharges, to meet the energy load demand at this time. After 15:00, due to the diminishing output

Table 1. Parameter descriptions

Parameters	Content	Value	Unit
η_{EGT}	Gas turbine electricity production efficiency	0.3	/
η_{HGT}	Gas turbine heat production efficiency	0.4	/
η_{WHB}	Efficiency coefficient of WHB	0.8	/
η_{ORC}	Efficiency coefficient of WHP	0.8	/
η_{HGB}	Gas boiler heat production efficiency factor	0.9	/
η_{HP}	Heat pump's coefficient of performance	4.4	/
$E_s^{\max}$	Maximum storage capacity of EES facility	8000	kWh
$E_{s,0}$	Initial storage capacity of the EES facility	1600	kWh
η_{sch}	EES facility charging efficiency	0.95	
η_{sdis}	EES facility discharge efficiency	0.9	
$H_{s,0}$	Initial storage capacity of the TES facility	1000	kWh
θ_{sch}	TES facility charging efficiency	0.95	
θ_{sdis}	TES facility discharging efficiency	0.9	
$E_{CHP,\max}$	Installed capacity of CHP unit	80000	kW
π_{GT}	Gas turbine O&M cost factor	0.04	RMB/kWh
π_{WHB}	O&M cost factor of WHB	0.025	RMB/kWh
π_{PV}	PV O&M cost factor	0.016	RMB/kWh
π_{WT}	Wind turbine O&M cost factor	0.018	RMB/kWh
π_{Es}	The O&M cost factor of EES	0.018	RMB/kWh
π_{Hs}	The O&M cost factor of TES	0.016	RMB/kWh
π_{CO2}	Carbon tax level	50	RMB/t
ϕ_g	Natural gas calorific value	9.88	kWh/m^3
P_g	Natural gas price	2.55	RMB/m^3
f_e	CHP unit carbon emission factor	610.1	g CO$_2$/ kWh
f_c	CO$_2$ capture efficiency (%)	0.85	

Table 2. Settings for the scenario

Scenario	Carbon tax	Carbon capture	Description	Notes
1	YES	NO	Carbon tax	• Electricity price: Peak tariff is 1.09 RMB/kWh; normal tariff is 0.68 RMB/kWh; valley tariff is 0.35 RMB/kWh (Zhenbo WEI et al., 2022). • Carbon tax: there is no carbon emission tax policy in China currently. According to Yu et al. (2022), the initial carbon tax collection standard is 50 RMB/tCO_2.
2	NO	YES	Carbon capture storage	
3	YES	YES	Carbon tax +Carbon capture storage	
4	NO	NO	/	

of PV, the purchase of power from the higher grid needs to be gradually increased to cover the load demand gap. During the second peak period of the energy load between 19:00 and 21:00, which is also the peak period of the time-of-use electricity price, the CHP unit needs to be started up again to work with the wind power and electricity storage to meet the load demand from the energy end-use.

Figure 5 illustrates the modeling outcome of the optimized dispatch of the CHP unit under different scenarios. Compared with Scenario 1 and Scenario 4, the CHP unit's power production decreases in the period when the renewable energy supply is abundant. additional carbon tax significantly reduces the dispatched power from the CHP unit. Comparing Scenario 2 and Scenario 4, it can be found that the CCS retrofitting of the CHP unit further limits the output of the CHP unit during the nighttime valley price hours and increases CHP unit output during the daytime peak price hours. It can be seen that the carbon tax and CCS retrofit will significantly inhibit CHP unit production because of the increased operating cost.

Table 3 shows the changes in the IES' overall operating costs and CO2 emissions for different scenarios over the simulation period. Both the carbon tax on the IES and the CCS retrofit will increase the operating expense of the IES compared to Scenario 4. In Scenario 1, the operating cost of the IES increases by 5.89% compared to Scenario 4. As a result, the output of CHP is limited, and the overall emissions of the system decrease by 53.67%. In Scenario 2, the CHP unit output is further reduced compared to Scenario 1, and the overall operating cost increases by 43.84%. However, compared to Scenario 4, the overall emissions of the IES in Scenario 2 decreased significantly by 92.88%.

Figure 4. Simulation results of optimized dispatch of IES under different scenarios

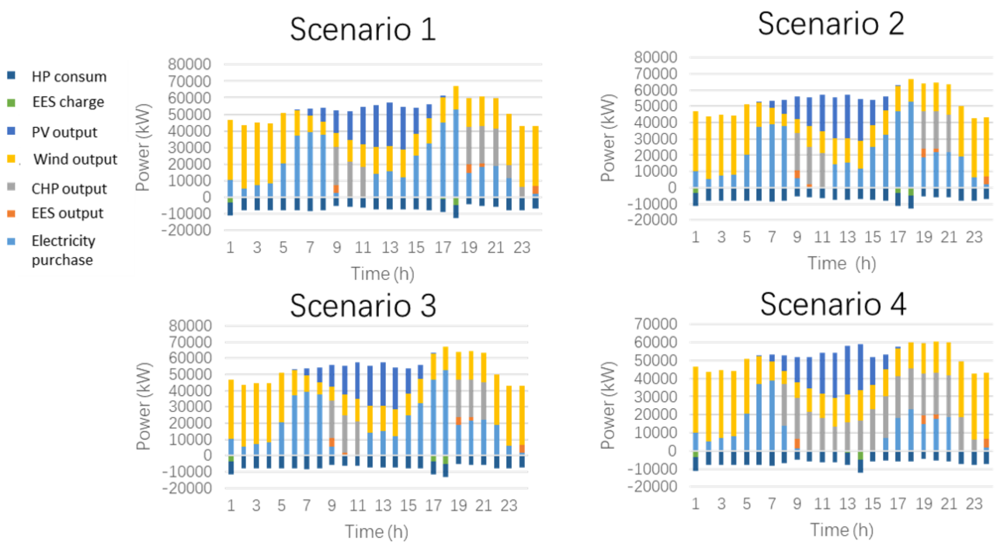


Figure 5. Optimal dispatch of CHP units under different scenarios

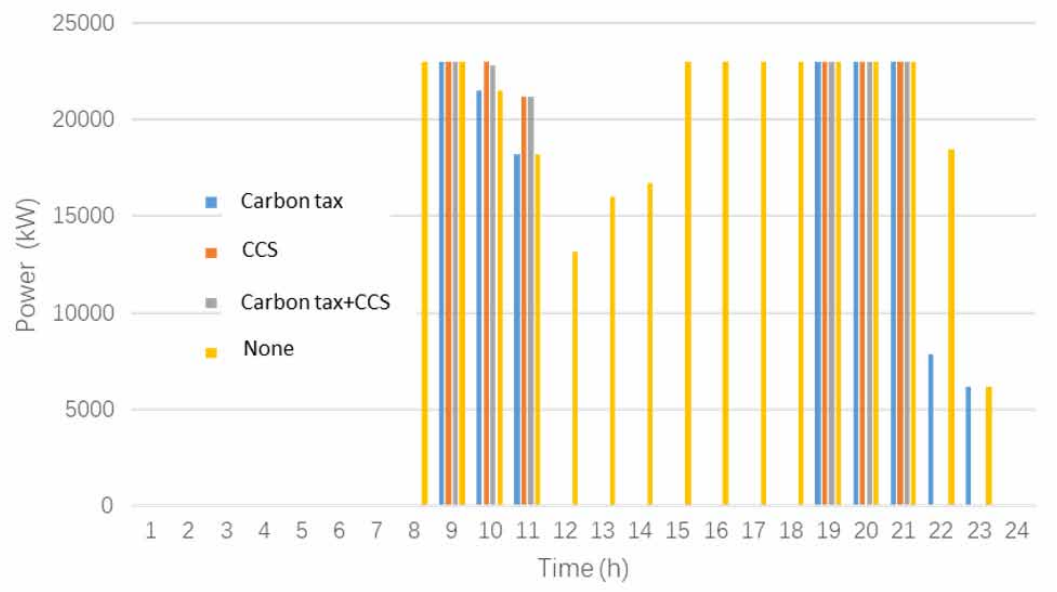


Table 3. Comparison of different scenarios

Scenario	Carbon tax	CCS	Total cost (RMB)	Carbon tax cost (RMB)	Total emission (t)	CHP output (kWh)	Change of total cost	Change of emission
1	√	×	3.99×10^5	11378.18	227.56	1.46×10^5	5.89%	-53.67%
2	×	√	5.42×10^5	0.00	34.95	1.36×10^5	43.84%	-92.88%
3	√	√	5.50×10^5	9033.70	34.91	1.36×10^5	46.19%	-92.89%
4	×	×	3.77×10^5	0.00	491.13	3.17×10^5	/	/

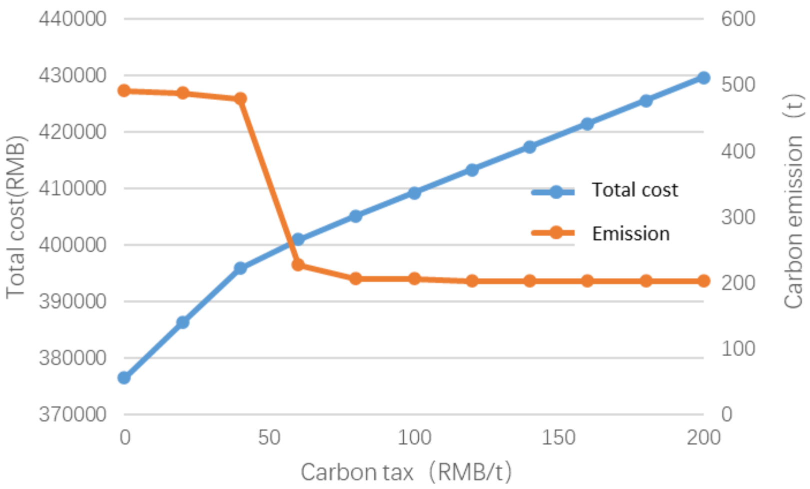
This shows that introducing low-carbon technologies has a better effect on emissions reduction than considering carbon tax alone as an emission regulation policy. There are mainly two reasons for the significant decrease in overall emissions in Scenario 2. On the one hand, the output of the CHP unit is limited due to the increased operating costs of the CHP unit caused by the CCS retrofit. On the other hand, the CCS technology also physically reduces the amount of CO_2 released from CHP flue gas significantly. The overall operating cost of Scenario 3 increases by 2.35% compared to Scenario 2 due to the additional carbon tax, but the overall carbon emissions decrease rate is only 0.01% higher. Considering both carbon taxes and carbon capture will increase the operating costs of integrated energy systems, with only a negligible contribution to emissions reductions.

4.2 Sensitivity Analysis

4.2.1 Effect of Carbon Tax Level on the Sensitivity of Overall Expenses and CO_2 Emissions (Considering Only Carbon Tax)

Figure 6 illustrates, in the case of considering only the carbon tax policy, how the overall operating costs and emissions of IES vary with the change in carbon tax. Considering the carbon tax alone, as the carbon tax increases, the overall operating expenses of the IES continue to rise. When the carbon tax exceeds 40 RMB/ ton, the growth in overall expenses will slow down slightly. When the carbon tax

Figure 6. Changes in system operation expenses and CO_2 emissions with carbon tax levels consider carbon tax only



level is between 0-40 RMB/ton, the CO_2 emission of the IES does not decrease significantly; When the carbon tax level is in the range of 40-60 RMB/ton, the carbon emission decreases significantly. As the carbon tax exceeded 100 RMB/ton, the system's carbon emissions remained virtually unchanged at approximately 203.06 tons.

As shown in Fig. 6, a non-linear relationship exists between the level of the carbon tax and overall system emissions. When the carbon tax level is less than 40 RMB/ton or more than 100 RMB/ton, the effect on the overall system emissions change is insignificant. A carbon tax that is too low may not have a significant policy regulatory effect. However, a higher carbon tax is not always better. A carbon tax level above a threshold will contribute little to reducing carbon emissions from an integrated energy system and may increase operating costs.

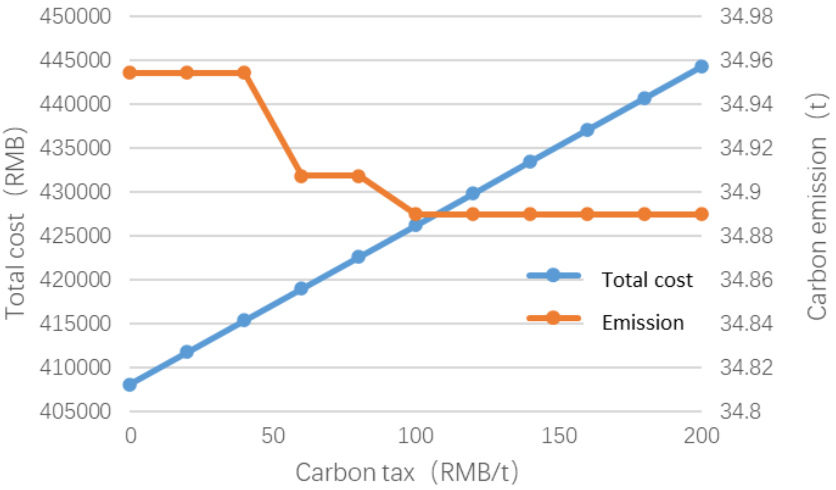
4.2.2 Sensitivity of Carbon Tax Level to Overall Expenses and CO_2 Emissions (Consider Carbon Tax and CCS Retrofit)

Figure 7 illustrates the case when both carbon tax policy and CCS retrofit are considered and how the overall operating costs and emissions of the IES vary with the change in carbon tax. Considering carbon tax and CCS, the overall expense of operating the system continues to rise as the carbon tax rises, as there is no sign of slowing down. When the carbon tax level exceeds 40 RMB/ton, the carbon emission of the system slightly decreases. When the level of carbon tax exceeds 100 RMB/ton, CO_2 emissions of IES remain almost unchanged at around 34.89 tons. The integrated energy system retrofitted by carbon capture is less sensitive to the carbon tax.

5 CONCLUSION AND POLICY IMPLICATIONS

This study extends the theoretical scope of basic IES simulation research. It incorporates CCS technology and carbon tax policy, examining the effectiveness and economic performance of CCS technology and carbon tax policies in the context of emissions reduction applications. Simulation results indicate that both CCS retrofitting and carbon tax policy can significantly decrease the overall carbon emissions of the system. However, the carbon tax and carbon capture retrofit increase the overall operation cost of the IES. Specifically, introducing the carbon tax mechanism increases the IES's operation cost by 5.89% while reducing carbon emissions by 53.67%. In the scenario of CCS

Figure 7. Changes in system operation expenses and CO_2 emissions with carbon tax levels consider carbon tax and CCS retrofit



retrofitting, the carbon emission of IES is reduced by 92.88%, while the operation cost of the IES increased by 43.84%. According to the sensitivity analysis, the overall cost of the IES rises rapidly at first as the level of carbon tax increases and then levels off when the carbon tax is solely considered. An increase in the level of carbon tax helps to reduce the overall emissions of the system, but after exceeding a certain critical value (100 RMB/ton in this case), the level of the carbon tax does not substantially reduce the system's emissions. The study broadens the relevant knowledge and research gap concerning dispatch management and facilitates scheduling optimization of the IES considering both carbon tax and CCS technology. This expansion is expected to provide theoretical insights and references for the subsequent construction and implementation of CCS technology, policy formulation, and further related research.

In terms of policy and managerial implications, Policymakers should recognize that the application of CCS technology is essential to achieve large-scale carbon emission reductions. It is difficult to achieve deep decarbonization of the IES by relying on carbon tax schemes solely. Policy support for CCS technology in R&D and diffusion should be strengthened. Based on the simulation results, the emission reduction cost incurred through CCS retrofit may lead to an increase of more than 40% in the operating cost of the IES. Therefore, it is recommended to alleviate the financial pressure of emission reduction and retrofitting of existing high-emission units and promote the renovation and deployment of CCS employing subsidies, differential tariff settlements, pilot projects, and the construction of a standardized system.

Furthermore, policymakers need to strive for a balanced approach between low-carbon development and economic objectives when formulating carbon tax policy. Establishing an appropriate carbon tax rate is crucial for the steady operation of the IES. The level of carbon taxation has a nonlinear impact on the overall emissions of the IES. Excessively high carbon tax does not reduce system emissions but significantly increases total IES operating costs. After the CCS retrofit, the total IES emissions are less sensitive to the carbon tax, and carbon tax exemption for the retrofitted CHP unit can be considered to reduce the pressure on the IES operating cost.

This paper also has limitations in the following aspects. The practical policy environment IES faces in the future will be complex and volatile. Besides carbon tax, policies such as tradeable green certificate, renewable portfolio standards, and carbon trading market may also affect the future operation mode of the IES. This study focuses on the typical intra-day operation situation regarding the simulation time interval. Thus, the discussion of the performance of IES over a longer period is neglected.

As for possible future research directions, a more complex policy environment should be further examined. The interactions and joint effects among different policies could be emphasized to obtain more realistic simulation results. As the electricity market reform progresses, new influencing factors such as electricity price fluctuation and demand-side response deserve to be considered. The operation and optimal dispatch characteristics of the IES in a longer time dimension are also worth further exploration.

ACKNOWLEDGMENT

This paper is supported by the National Natural Science Foundation of China (Key Program, No 72133003), and the Key Projects of Philosophy and Social Sciences Research, Ministry of Education, (Grant No.: 22JZD008).

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

AlHajri, I., Ahmadian, A., & Elkamel, A. (2021). Techno-economic-environmental assessment of an integrated electricity and gas network in the presence of electric and hydrogen vehicles: A mixed-integer linear programming approach. *Journal of Cleaner Production*, *319*, 128578. doi:10.1016/j.jclepro.2021.128578

Bank, W. (2022). State and Trends of Carbon Pricing 2022. http://hdl.handle.net/10986/37455

Cai, B., Li, Q., & Zhang, X. (2021). *Annual report of carbon capture, utilization and storage (CCUS) in China 2021.* Chinese Academy of Environmental Planning, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, The Administrative Center for China's Agenda 21.

Cao, M., Shao, C., Hu, B., Xie, K., Zhou, J., Leng, H., & Zhang, W. (2022). Reliability tracing of the integrated energy system using the improved shapley value. *Energy*, *260*, 124997. doi:10.1016/j.energy.2022.124997

Carroll, D. A., & Stevens, K. A. (2021). The short-term impact on emissions and federal tax revenue of a carbon tax in the U.S. electricity sector. *Energy Policy*, *158*, 112526. doi:10.1016/j.enpol.2021.112526

Cau, G., Tola, V., Ferrara, F., Porcu, A., & Pettinau, A. (2018). CO2-free coal-fired power generation by partial oxy-fuel and post-combustion CO2 capture: Techno-economic analysis. *Fuel*, *214*, 423–435. doi:10.1016/j.fuel.2017.10.023

Cui, L., Li, R., Song, M., & Zhu, L. (2019). Can China achieve its 2030 energy development targets by fulfilling carbon intensity reduction commitments? *Energy Economics*, *83*, 61–73. doi:10.1016/j.eneco.2019.06.016

Ding, Y., Tan, Q., Shan, Z., Han, J., & Zhang, Y. (2023). A two-stage dispatching optimization strategy for hybrid renewable energy system with low-carbon and sustainability in ancillary service market. *Renewable Energy*, *207*, 647–659. doi:10.1016/j.renene.2023.03.050

Du, Z., Zheng, L., & Lin, B. (2022). Does Rent-Seeking Affect Environmental Regulation?: Evidence From the Survey Data of Private Enterprises in China. [JGIM]. *Journal of Global Information Management*, *30*(6), 1–22. doi:10.4018/JGIM.288549

González-Carrasco, V., Robina-Ramírez, R., Gibaja-Romero, D.-E., & Sánchez, M. S.-O. (2023). The Quintuple Helix Model: Cooperation system for a sustainable electric power industry in Mexico. *Frontiers in Sustainable Energy Policy*, *1*, 1047675. doi:10.3389/fsuep.2022.1047675

Guo, R., Ye, H., & Zhao, Y. (2022). Low carbon dispatch of electricity-gas-thermal-storage integrated energy system based on stepped carbon trading. *Energy Reports*, *8*, 449–455. doi:10.1016/j.egyr.2022.09.198

Gustafsson, K., Sadegh-Vaziri, R., Grönkvist, S., Levihn, F., & Sundberg, C. (2021). BECCS with combined heat and power: Assessing the energy penalty. *International Journal of Greenhouse Gas Control*, *108*, 103248. doi:10.1016/j.ijggc.2020.103248

He, L., Lu, Z., Zhang, J., Geng, L., Zhao, H., & Li, X. (2018). Low-carbon economic dispatch for electricity and natural gas systems considering carbon capture systems and power-to-gas. *Applied Energy*, *224*, 357–370. doi:10.1016/j.apenergy.2018.04.119

Huang, Y., Wang, Y., & Liu, N. (2022). Low-carbon economic dispatch and energy sharing method of multiple Integrated Energy Systems from the perspective of System of Systems. *Energy*, *244*, 122717. doi:10.1016/j.energy.2021.122717

Jia, Z., Lin, B., & Liu, X. (2023). Rethinking the equity and efficiency of carbon tax: A novel perspective. *Applied Energy*, *346*, 121347. doi:10.1016/j.apenergy.2023.121347

Jin, J., Zhou, D., Zhou, P., & Miao, Z. (2014). Environmental/economic power dispatch with wind power. *Renewable Energy*, *71*, 234–242. doi:10.1016/j.renene.2014.05.045

Jin, J., Zhou, P., Li, C., Bai, Y., & Wen, Q. (2020). Optimization of power dispatching strategies integrating management attitudes with low carbon factors. *Renewable Energy*, *155*, 555–568. doi:10.1016/j.renene.2020.03.174

Jin, J., Zhou, P., Li, C., Guo, X., & Zhang, M. (2019). Low-carbon power dispatch with wind power based on carbon trading mechanism. *Energy*, *170*, 250–260. doi:10.1016/j.energy.2018.12.126

Kim, H., Kim, Y. H., Kang, S.-G., & Park, Y.-G. (2016). Development of environmental impact monitoring protocol for offshore carbon capture and storage (CCS): A biological perspective. *Environmental Impact Assessment Review*, *57*, 139–150. doi:10.1016/j.eiar.2015.11.004

Kotagodahetti, R., Hewage, K., Karunathilake, H., & Sadiq, R. (2022). Long-term feasibility of carbon capturing in community energy systems: A system dynamics-based evaluation. *Journal of Cleaner Production*, *377*, 134460. doi:10.1016/j.jclepro.2022.134460

Li, J., & Ho, M. S. (2022). Indirect cost of renewable energy: Insights from dispatching. *Energy Economics*, *105*, 105778. doi:10.1016/j.eneco.2021.105778

Li, K., Yang, J., & Wei, Y. (2023). Impacts of carbon markets and subsidies on carbon capture and storage retrofitting of existing coal-fired units in China. *Journal of Environmental Management*, *326*, 116824. doi:10.1016/j.jenvman.2022.116824 PMID:36442336

Lin, B., & Ma, R. (2022). How Does Internet Development Affect Green Technology Innovation in China? [JGIM]. *Journal of Global Information Management*, *30*(1), 1–21. doi:10.4018/JGIM.309081

Lin, B., & Tan, Z. (2021). How much impact will low oil price and carbon trading mechanism have on the value of carbon capture utilization and storage (CCUS) project? Analysis based on real option method. *Journal of Cleaner Production*, *298*, 126768. doi:10.1016/j.jclepro.2021.126768

Lin, B., & Tan, Z. (2023). Exploring arbitrage opportunities between China's carbon markets based on statistical arbitrage pairs trading strategy. *Environmental Impact Assessment Review*, *99*, 107041. doi:10.1016/j.eiar.2023.107041

Liu, S., Wei, N., Jiang, D., Nie, L., Cai, B., Tao, Y., & Li, X. (2023). Emission reduction path for coal-based enterprises via carbon capture, geological utilization, and storage: China energy group. *Energy*, *273*, 127222. doi:10.1016/j.energy.2023.127222

Liu, Z.-F., Li, L.-L., Liu, Y.-W., Liu, J.-Q., Li, H.-Y., & Shen, Q. (2021). Dynamic economic emission dispatch considering renewable energy generation: A novel multi-objective optimization approach. *Energy*, *235*, 121407. doi:10.1016/j.energy.2021.121407

Lyu, X., Liu, T., Liu, X., He, C., Nan, L., & Zeng, H. (2023). Low-carbon robust economic dispatch of park-level integrated energy system considering price-based demand response and vehicle-to-grid. *Energy*, *263*, 125739. doi:10.1016/j.energy.2022.125739

Ma, S.-C., Yi, B.-W., & Fan, Y. (2022). Research on the valley-filling pricing for EV charging considering renewable power generation. *Energy Economics*, *106*, 105781. Advance online publication. doi:10.1016/j.eneco.2021.105781

Mansourshoar, P., Yazdankhah, A. S., Vatanpour, M., & Mohammadi-Ivatloo, B. (2022). Impact of implementing a price-based demand response program on the system reliability in security-constrained unit commitment problem coupled with wind farms in the presence of contingencies. *Energy*, *255*, 124333. doi:10.1016/j.energy.2022.124333

Pappas, D., Braunholtz-Speight, T., Hannon, M., Webb, J., González, F. F., & Sharmina, M. (2023). Business models for smart local energy systems—A triple layered perspective. *Frontiers in Sustainable Energy Policy*, *1*, 1058534. doi:10.3389/fsuep.2022.1058534

Su, H., Zio, E., Zhang, J., Li, Z., Wang, H., Zhang, F., Chi, L., Fan, L., & Wang, W. (2020). A systematic method for the analysis of energy supply reliability in complex Integrated Energy Systems considering uncertainties of renewable energies, demands and operations. *Journal of Cleaner Production*, *267*, 122117. doi:10.1016/j.jclepro.2020.122117

Tan, Q., Ding, Y., Zheng, J., Dai, M., & Zhang, Y. (2021). The effects of carbon emissions trading and renewable portfolio standards on the integrated wind–photovoltaic–thermal power-dispatching system: Real case studies in China. *Energy*, *222*, 119927. doi:10.1016/j.energy.2021.119927

Tan, Q., Mei, S., Ye, Q., Ding, Y., & Zhang, Y. (2019). Optimization model of a combined wind–PV–thermal dispatching system under carbon emissions trading in China. *Journal of Cleaner Production*, *225*, 391–404. doi:10.1016/j.jclepro.2019.03.349

Tan, Z., Zeng, X., & Lin, B. (2023). How do multiple policy incentives influence investors' decisions on biomass co-firing combined with carbon capture and storage retrofit projects for coal-fired power plants? *Energy*, *278*, 127822. doi:10.1016/j.energy.2023.127822

Tarufelli, B., Snyder, B., & Dismukes, D. (2021). The Potential Impact of the U.S. Carbon Capture and Storage Tax Credit Expansion on the Economic Feasibility of Industrial Carbon Capture and Storage. *Energy Policy*, *149*, 112064. doi:10.1016/j.enpol.2020.112064

Wang, H., & Wang, L. (2022). Product line strategy and environmental impact oriented to carbon tax constraints. *Sustainable Production and Consumption*, *32*, 198–213. doi:10.1016/j.spc.2022.04.015

Wang, R., Wen, X., Wang, X., Fu, Y., & Zhang, Y. (2022). Low carbon optimal operation of integrated energy system based on carbon capture technology, LCA carbon emissions and ladder-type carbon trading. *Applied Energy*, *311*, 118664. doi:10.1016/j.apenergy.2022.118664

Wang, X., Tang, R., Meng, M., & Su, T. (2023). Research on CCUS business model and policy incentives for coal-fired power plants in China. *International Journal of Greenhouse Gas Control*, *125*, 103871. doi:10.1016/j.ijggc.2023.103871

Wei, Z., Ren, X., & Huang, Y. (2020). Multi-Objective Optimal Dispatch for Integrated Energy System Considering Integrated Demand Response. *Electric Power Construction*, *41*(7), 92–99.

Wei, Z., Ma, X., Guo, Y., Wei, P., Lu, B., & Zhang, H. (2022). Optimized Operation of Integrated Energy System Considering Demand Response under Carbon Trading Mechanism. [in Chinese]. *Electric Power Construction*, *43*(01), 1–9.

Wesseh, P. K. Jr, & Lin, B. (2022). A time-of-use pricing model of the electricity market considering system flexibility. *Energy Reports*, *8*, 1457–1470. doi:10.1016/j.egyr.2021.12.027

Xie, H., Sun, X., Fu, W., Chen, C., & Bie, Z. (2023). Risk management for integrated power and natural gas systems against extreme weather: A coalitional insurance contract approach. *Energy*, *263*, 125750. doi:10.1016/j.energy.2022.125750

Xu, Z., Sun, Y., Xie, D., Wang, J., & Zhong, Y. (2020). Optimal Configuration of Energy Storage for Integrated Region Energy System Considering Power. *Thermal Flexible Load*, *44*(2), 53-59.

Xu, C., Xu, Y., Chen, J., Huang, S., Zhou, B., & Song, M. (2023). Spatio-temporal efficiency of fiscal environmental expenditure in reducing CO2 emissions in China's cities. *Journal of Environmental Management*, *334*, 117479. doi:10.1016/j.jenvman.2023.117479 PMID:36780813

Yamchi, H. B., Safari, A., & Guerrero, J. M. (2021). A multi-objective mixed integer linear programming model for integrated electricity-gas network expansion planning considering the impact of photovoltaic generation. *Energy*, *222*, 119933. doi:10.1016/j.energy.2021.119933

Yang, L., Xu, M., Fan, J., Liang, X., Zhang, X., Lv, H., & Wang, D. (2021). Financing coal-fired power plant to demonstrate CCS (carbon capture and storage) through an innovative policy incentive in China. *Energy Policy*, *158*, 112562. doi:10.1016/j.enpol.2021.112562

Yang, L., Xu, M., Yang, Y., Fan, J., & Zhang, X. (2019). Comparison of subsidy schemes for carbon capture utilization and storage (CCUS) investment based on real option approach: Evidence from China. *Applied Energy*, *255*, 113828. doi:10.1016/j.apenergy.2019.113828

Yang, S., Tan, Z., Lin, H., Li, P., De, G., Zhou, F., & Ju, L. (2020). A two-stage optimization model for Park Integrated Energy System operation and benefit allocation considering the effect of Time-Of-Use energy price. *Energy*, *195*, 117013. doi:10.1016/j.energy.2020.117013

Yao, X., Fan, Y., Zhao, F., & Ma, S.-C. (2022). Economic and climate benefits of vehicle-to-grid for low-carbon transitions of power systems: A case study of China's 2030 renewable energy target. *Journal of Cleaner Production*, *330*, 129833. doi:10.1016/j.jclepro.2021.129833

Yu, F., Chu, X., Sun, D., & Liu, X. (2022). Low-carbon economic dispatch strategy for renewable integrated power system incorporating carbon capture and storage technology. *Energy Reports*, *8*, 251–258. doi:10.1016/j.egyr.2022.05.196

Zhang, X., Guo, X., & Zhang, X. (2023). Bidding modes for renewable energy considering electricity-carbon integrated market mechanism based on multi-agent hybrid game. *Energy*, *263*, 125616. doi:10.1016/j.energy.2022.125616

Zhang, Y., Zhang, X., & Ng, T. S. (2021). Analysis of the carbon-gas-electricity trigger price for carbon capture and power-to-gas coupling system. *Sustainable Production and Consumption*, *28*, 1164–1177. doi:10.1016/j.spc.2021.07.035

Zhao, K., Jia, C., Li, Z., Du, X., Wang, Y., Li, J., Yao, Z., & Yao, J. (2023). Recent Advances and Future Perspectives in Carbon Capture, Transportation, Utilization, and Storage (CCTUS) Technologies: A Comprehensive Review. *Fuel*, *351*, 128913. doi:10.1016/j.fuel.2023.128913

Zhu, L., Ren, H., Habibi, M., Mohammed, K. J., & Khadimallah, M. A. (2022). Predicting the environmental economic dispatch problem for reducing waste nonrenewable materials via an innovative constraint multi-objective Chimp Optimization Algorithm. *Journal of Cleaner Production*, *365*, 132697. doi:10.1016/j.jclepro.2022.132697

Zhizhou Tan is a Ph.D. candidate of China Institute for Studies in Energy Policy, School of Management, Xiamen University. His research interests are energy economics, technical economics and management.

Boqiang Lin is the corresponding author of this article. He obtained a Ph.D. degree in Economics from the University of California, Santa Barbara. He is a "Changjiang Scholar" Distinguished Professor, honored by the Ministry of Education of China in 2007. He is the Dean of China Institute for Studies in Energy Policy, Xiamen University; a Chief Scientist of Tan Kah Kee Innovation Laboratory; and a Distinguished Researcher at the State Key Laboratory of Physical Chemistry of Solid Surfaces. His research and teaching focus on energy economics, management, and policy. He aims to cultivate Ph.D. graduates for academic positions at prestigious universities under the 985/211 initiatives and famous financial and economic institutions. His research is guided by addressing national major demands and solving practical problems, to enhance support for national energy policies and public influence.