

# Co-optimization of Carbon Reduction and Carbon Sequestration in Power Sector Toward Carbon Neutrality

Mingyu Yang, Yusheng Xue, Bin Cai, and Feng Xue

**Abstract**—Planning the low-carbon transition pathway of the power sector to meet the carbon neutrality goal poses a significant challenge due to the complex interplay of temporal, spatial, and cross-domain factors. A novel framework is proposed, grounded in the cyber–physical–social system in energy (CPSSE) and whole-reductionism thinking (WRT), incorporating a tailored mathematical model and optimization method to formalize the co-optimization of carbon reduction and carbon sequestration in the power sector. Using the carbon peaking and carbon neutrality transition of China as a case study, clustering method is employed to construct a diverse set of strategically distinct carbon trajectories. For each trajectory, the evolution of the generation mix and the deployment pathways of carbon capture and storage (CCS) technologies are analyzed, identifying the optimal transition pathway based on the criterion of minimizing cumulative economic costs. Further, by comparing non-fossil energy substitution and CCS retrofitting in thermal power, the analysis highlights the potential for co-optimization of carbon reduction and carbon sequestration. The results demonstrate that leveraging the spatiotemporal complementarities between the two can substantially lower the economic cost of achieving carbon neutrality, providing insights for integrated decarbonization strategies in power system planning.

**Index Terms**—Whole-reductionism thinking, low-carbon transition, carbon reduction, carbon sequestration, carbon peaking, carbon neutrality, co-optimization.

## I. INTRODUCTION

THE power system, as the central hub of the energy chain, plays a vital role in supporting socio-economic

development while also shouldering the responsibility of achieving carbon peaking and carbon neutrality goals [1].

Existing research on low-carbon transition pathways in the power sector generally falls into three categories. The first category is linear programming (LP), which models the transition as a linear optimization problem. For instance, [2] utilizes the CPLEX solver to analyze low-carbon transition of power sector in China in three scenarios: low-carbon, zero-carbon, and negative-carbon. LP methods benefit from mature algorithms and solver packages, but often oversimplify technical specifications to enable mathematical tractability. The second category involves computable general equilibrium (CGE) models, which assume the optimal economic behavior to derive equilibrium solutions at each time step, simulating future development scenarios. As an example, [3] applies the China-Global Energy Model (C-GEM) to explore energy-economic pathways of China toward carbon neutrality. CGE models effectively capture interactions between the power sector and broader economy, yet their reliance on idealized assumptions and lack of engineering detail limit their practical applicability [4]. A more flexible approach is the candidate pathway comparison (CPC) method, which constructs a feasible set of carbon trajectories within an indicator plane. These pathways are then evaluated step-by-step, allowing the high-dimensional dynamics to be linearized locally, and optimal trajectories are selected based on economic cost [5]. CPC method is particularly suitable for handling nonlinearities, irrational behaviors, and uncertainties. Recent applications of this method span national [6], regional [7], and enterprise-level [8] electricity transition studies, as well as in the exploration of specific generation technologies [9], [10].

In the context of global climate governance, there is growing recognition among scholars and policymakers that achieving net-zero emissions through renewable energy alone poses significant challenges. A diversified technological mix is more effective in promoting carbon neutrality [11]–[13]. Carbon reduction and carbon sequestration, as complementary “source” and “sink” strategies, serve distinct roles in the decarbonization process. However, the majority of current planning studies classify carbon sequestration as a form of (negative) carbon emission, incorporating it into the broader category of carbon reduction. These studies typically rely on time-specific marginal abatement cost (MAC) met-

Manuscript received: October 16, 2024; revised: February 8, 2025; accepted: April 14, 2025. Date of CrossCheck: April 14, 2025. Date of online publication: May 2, 2025.

This work was supported in part by the State Grid Corporation of China (SGCC) “Research on the Sand-table Deduction and Risk Decision-making Technology of the Power System Actively Supporting the Energy Transition and Dual-carbon Revolution” (No. 524608220268).

This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>).

M. Yang and Y. Xue (corresponding author) are with the School of Electrical Engineering, Shandong University, Jinan, China, and they are also with State Grid Electric Power Research Institute (NARI Group Corporation), Nanjing, China, and Y. Xue is also with State Key Laboratory of Smart Grid Protection and Operation Control, Nanjing, China (e-mail: 201600190230@mail.sdu.edu.cn; xueyusheng@sgepri.sgcc.com.cn).

B. Cai and F. Xue are with State Grid Electric Power Research Institute (NARI Group Corporation), Nanjing, China, and they are also with State Key Laboratory of Smart Grid Protection and Operation Control, Nanjing, China (e-mail: caibin@sgepri.sgcc.com.cn; xue-feng@sgepri.sgcc.com.cn).

DOI: 10.35833/MPCE.2024.001135



rics to generate transition pathways, neglecting the substantial differences in technical maturity, functional characteristics, and economic profiles between the two methods, which ultimately leads to a misalignment between development pathways and their specific stages and attributes.

To address these issues, recent research has introduced a decomposition framework that structurally separates the system into two interdependent subsystems: carbon reduction and carbon sequestration. These subsystems are intricately coupled with each other and with external systems. Thus, their mutual constraints and synergies must be carefully evaluated in optimization modeling. Reference [14] proposes a whole-reductionism approach for carbon peaking and carbon neutrality transition pathways, providing a framework and tools to analyze the evolutionary behaviors and mechanisms of carbon reduction and carbon sequestration toward carbon neutrality. Building on this, this study aims to further explore co-optimization between carbon reduction and carbon sequestration toward carbon neutrality. The main contributions of this paper can be summarized as follows.

1) A systematic methodology is proposed for the co-optimization of carbon reduction and carbon sequestration in the power sector. Guided by the cyber-physical-social system in energy (CPSSE) and whole-reductionism thinking (WRT), this study addresses the inherent complexities arising from spatial heterogeneity, temporal dynamics, and interconnections across domains in optimizing transition pathways toward carbon neutrality. An optimization framework is developed that facilitates both internal optimization and aggregated coordination of carbon reduction and carbon sequestration, within a dual-layer architecture for target and pathway optimization.

2) A comprehensive mathematical model is developed to minimize the cumulative economic costs of power supply and carbon capture and storage (CCS) deployment during the transition period. The model incorporates constraints related to system safety, technological feasibility, economic affordability, and environmental impact.

3) The optimization of low-carbon transition pathways of power sector is integrated with the broader strategy for achieving carbon peaking and carbon neutrality goals. By clustering multiple realistic and strategically distinct candidate pathways on a two-dimensional decision-making plane, which is defined by carbon emission and carbon sequestration, this study quantitatively analyzes their impact on generation mix evolution, CCS deployment patterns, and transition costs. This approach highlights the synergistic potential between carbon reduction and carbon sequestration in the power sector, advancing the focus from isolated optimization of the low-carbon transition of power sector to a comprehensive alignment with the carbon peaking and carbon neutrality goal of the whole society.

## II. FRAMEWORK FOR CO-OPTIMIZATION OF CARBON REDUCTION AND CARBON SEQUESTRATION FOR WHOLE SOCIETY

The optimization problem of carbon reduction and carbon sequestration at the societal level is decoupled into two hier-

archical levels. In the first level, adopting a social planner perspective, entities responsible for implementing the low-carbon transition, such as nations or regions, are considered as a unified whole. Utilizing the CPC method, a comprehensive evaluation is conducted on the costs associated with carbon reduction and carbon sequestration measures. Through a comparative analysis, the optimal physical trajectory for the low-carbon transition is determined, aiming to minimize total economic costs. This includes both long-term power infrastructure expansion and short-term operational plans.

Building upon this foundation, the second level addresses the impact of social factors such as policies (e.g., renewable energy subsidies, carbon quotas, equivalent quantity adjustments) and the behavior of market participants. This level employs a hybrid simulation model focused on designing precise policies and market mechanisms that effectively guide and incentivize market participants' long-term investments in carbon reduction and carbon sequestration projects, as well as their short-term market trading behaviors, in alignment with the low-carbon transition pathway derived from the first-level optimization [15]. This paper primarily focuses on the first level of the research, establishing an interactive interface between the system model and the power and carbon markets.

In [5], a two-dimensional decision-making plane is introduced, where carbon emissions are plotted on the horizontal axis and carbon sequestration on the vertical axis to illustrate the carbon peaking and carbon neutrality transition pathways in the first quadrant. The evolutionary time functions as an implicit parameter for trajectory mapping. Reference [14] further introduces a formalized approach to represent the tasks of achieving carbon peaking and carbon neutrality on this two-dimensional decision-making plane. It also defines key concepts, including initial carbon state, terminal carbon state, carbon trajectory (the evolutionary pathway connecting the initial and terminal carbon states), and critical neutrality domain.

Building on the proposed framework, this study defines a set of strategically distinct terminal carbon states on the two-dimensional decision-making plane, forming a candidate pool. For each terminal carbon state, multiple carbon trajectories are mapped from a common initial carbon state to the designated terminal carbon state, clustering all feasible evolutionary pathways into a finite number of representative trajectories. This approach constructs a candidate set of carbon trajectories that are tailored to each specific terminal carbon state.

A dual-layer optimization architecture for target and pathway [16] is adopted, utilizing a nested loop structure to evaluate all candidate pathways. In the inner loop, each pathway corresponding to the same terminal carbon state is quantitatively assessed across economic, safety, and environmental factors, with a focus on monetization. This evaluation facilitates the selection of the optimal pathway for each terminal carbon state, reflecting the performance of the corresponding terminal carbon state. The outer loop iterates through all terminal carbon states within the candidate set, identifying the optimal target state and its corresponding optimal pathway.

This paper reformulates the carbon neutrality pathway optimization problem as the internal optimization of carbon reduction and carbon sequestration measures, along with their aggregated coordination. During the pathway evaluation process, the temporal trajectories of carbon emission and sequestration are separately fed into two sub-modules: carbon reduction pathway optimization and carbon sequestration pathway optimization. These sub-modules, based on the pathway mapping on the two-dimensional decision-making plane, sequentially search for the optimal implementation strategies for carbon reduction and carbon sequestration over time within the measurement space. The optimization results are then stored for subsequent comparative analysis.

Specifically, the carbon reduction pathway optimization sub-module utilizes the temporal trajectory of carbon emissions as input and optimizes the allocation of emission budgets across sectors. Each sector, while adhering to the carbon budget constraints, optimizes its pathway over time to minimize carbon reduction costs. Meanwhile, the carbon sequestration pathway optimization sub-module, using the temporal trajectory of carbon sequestration as input, optimizes the allocation of sequestration demands between technological and natural approaches. Both sequestration approaches are optimized stepwise over time to minimize carbon sequestration costs while meeting sequestration targets. The diagram of the co-optimization framework for carbon reduction and carbon sequestration is depicted in Fig. 1.

### III. OPTIMIZATION METHOD FOR LOW-CARBON TRANSITION PATHWAYS IN POWER SECTOR BASED ON WRT

Reference [17] proposes constructing a simulation model to abstract and replicate the objective structure of the system. Numerical simulation yields temporal trajectories of system variables during the evolutionary process. The extracted quantitative data serve as a solid foundation for decision support.

#### A. Alleviation of Domain Complexity

Carbon peaking and carbon neutrality constitute a complex system spanning the energy, economic, and environmental domains, with carbon reduction and carbon sequestration in the power sector as critical components.

In numerical simulations, cross-domain models are developed to analyze carbon peaking and carbon neutrality transition pathways, generating evolutionary trajectories that capture the holistic dynamics of the system and provide mechanistic insights. These models couple subsystems across different domains, requiring careful consideration of interactions among heterogeneous domain models. The selection of boundary variables is essential for successful integration of these cross-domain models.

Regarding optimization, a decoupled optimization and aggregated coordination approach is employed. The decoupling dimensions encompass the relationships between the carbon peaking and carbon neutrality goal and the energy transition, the energy transition and the electricity transition, the grid planning and the operational analysis, as well as the security and the adequacy in grid operation analysis.

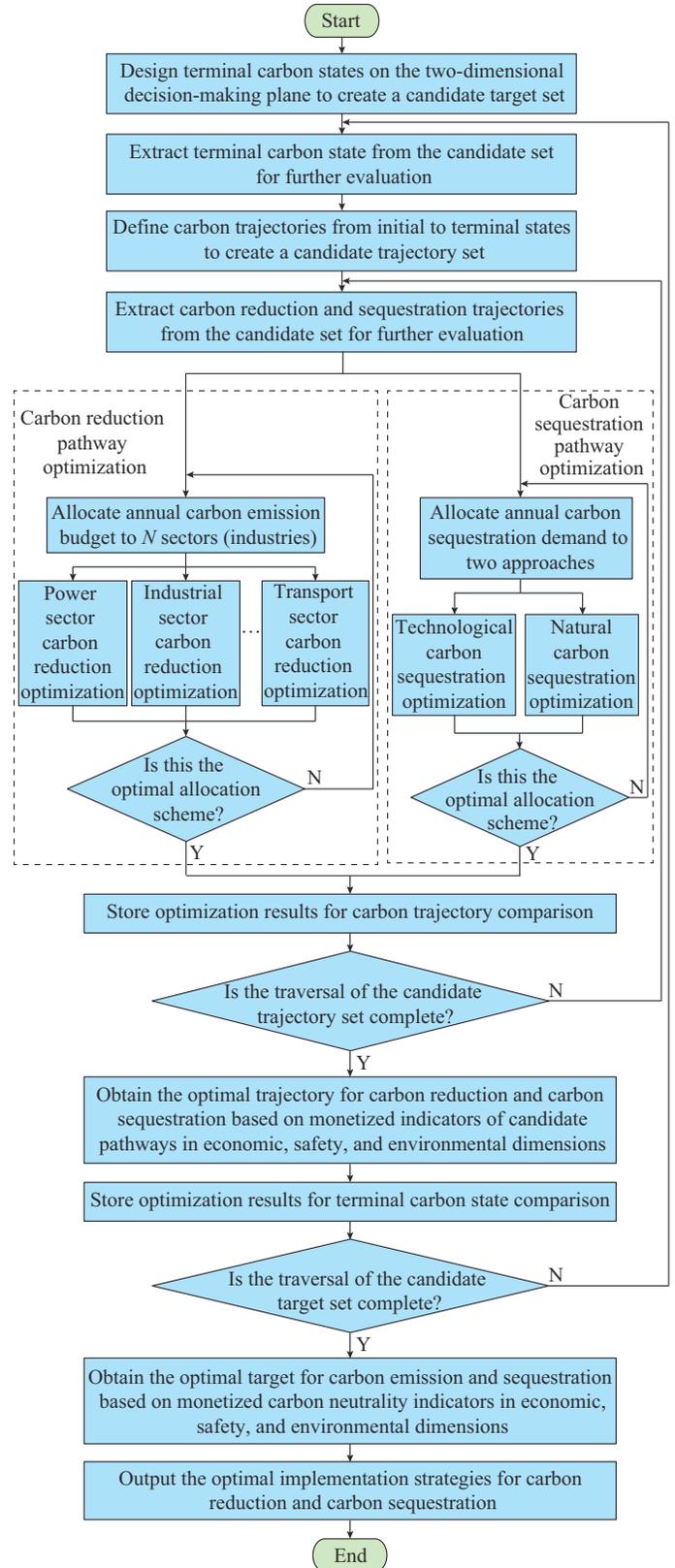


Fig. 1. Diagram of co-optimization framework for carbon reduction and carbon sequestration.

These optimization layers are not loosely parallel but are interconnected. Micro-level optimization results are embedded in the macro-level optimization process, where each step

of the macro-level optimization aggregates the micro-level outcomes to guide further optimization. This ensures good scalability when additional optimization layers are integrated.

Given the crucial role of power sector in achieving broader societal carbon peaking and carbon neutrality goals, its transition strategies must be systematically derived from these overarching goals. The power sector supports societal carbon peaking and carbon neutrality goals by facilitating the shift from direct coal, oil, and gas consumption to electricity, while restructuring its energy mix to meet carbon reduction targets. Following the determination of low-carbon transition pathways for the power sector, the effects of power expansion decisions at each time step are simulated [18]. This simulation assesses operational risks arising from various physical constraints, including system security and adequacy. When these risks exceed predefined thresholds, investments in infrastructure expansion (e.g., storage systems) are triggered. By comparing the risk mitigation effects of different investment plans, the optimal strategy is identified to minimize transition costs while adhering to risk threshold constraints.

Specifically, for system security optimization, key factors such as renewable energy output, load, and hydropower availability are extracted to define typical annual load flow conditions. Disturbances are selected from the disturbance library, and emergency control strategies are formulated, along with security risk assessments based on fault probabilities. Based on these evaluations, the grid operation and infrastructure investment strategies are optimized, ultimately yielding annual security optimization results.

For system adequacy optimization, the problem of minimizing annual operational risks is decoupled into optimization scheduling for multiple daily operating conditions. These daily operational strategies account for both internal demand and external power flow transmission. Subsequently, based on power flow constraints, the capacity allocation and regulation strategies for generation, storage, grids, and loads are optimized, including new regulation strategies such as energy storage, hydrogen energy, and demand-side management for peak shaving and backup. Finally, the operational risks for each condition are quantified and aggregated to derive the annual operational risk.

### *B. Alleviation of Spatial Complexity*

In numerical simulations, this study employs a decoupling and dimensionality reduction approach to simplify the analysis into two interrelated subsystems, i.e., carbon reduction and carbon sequestration subsystems, while preserving the coupling relationships. The carbon reduction and carbon sequestration subsystems of the power sector are then analyzed in detail, and their characteristic indicators are aggregated to comprehensively depict the evolution and underlying mechanisms of the system in pursuit of carbon peaking and carbon neutrality goals.

For optimization methods, the original problem is reformulated as an internal optimization of carbon reduction and carbon sequestration measures, along with their aggregated coordination. This approach facilitates the tailored development

of carbon reduction and carbon sequestration technologies, accounting for their respective stages of development and unique characteristics. For instance, in the early stages of the transition, high-cost yet essential carbon sequestration technologies are incentivized, allowing them to be balanced with carbon reduction technologies in the later stages of the transition. By leveraging the temporal and spatial complementarity of carbon reduction and carbon sequestration across technical, economic, and environmental dimensions, this approach minimizes economic costs for achieving carbon neutrality.

### *C. Alleviation of Temporal Complexity*

The carbon reduction and carbon sequestration pathways in the power sector can be divided into multiple interrelated stages, each requiring decisions based on the current state and influencing future developments. The sequence of decisions determines the implementation pathway for carbon reduction and carbon sequestration. This multi-stage decision-making process, with a chain structure linking past and future decisions, gives rise to significant nonlinear relationships between the decision variables and their interactions with the objective function and constraints. For instance, investment decisions for coal-fired power plants require several years of construction before integration into the grid, resulting in an asynchronous relationship between decisions and their effects, which induces nonlinear coupling. The application of CCS technology has facilitated technological advancements, leading to a reduction in costs, thereby generating positive feedback effects. Furthermore, when the proportion of wind or photovoltaic (PV) power within the system becomes excessively high, it exacerbates the temporal and spatial mismatch between supply and demand, thereby hindering the expansion of similar power sources and creating a negative feedback effect.

In numerical simulation, the temporal trajectories of external boundary variables related to carbon reduction and carbon sequestration in the power sector are incorporated. A piecewise linearization approach is then applied, treating each small time interval as a closed linearized system. This method transforms the complex nonlinear system into a linearizable and computationally manageable form. Through stepwise numerical simulations, the time series of characteristic indicators are obtained, revealing the evolutionary mechanisms of carbon reduction and carbon sequestration in the power sector.

Regarding optimization methods, instead of using conventional algorithms that generate pathways based on cost-effective reduction or sequestration measures at each step, this study clusters candidate pathways and evaluates their economic costs to identify the optimal one. Since the pathway optimization in this study is based on the evaluation of the entire trajectory, it enables holistic coordination across the full-time domain, thus avoiding local optima that may arise from sectional information optimization and hinder the attainment of a truly optimal solution.

### *D. Alleviation of High-dimensional Uncertainty*

Research on electricity transition pathways encompasses

various fields and requires extensive data. The reliability of the research outcomes is influenced by multiple uncertainties, including both internal factors and external conditions of the power system, over short- and long-term timeframes.

In numerical simulations, the input scenario parameters reflect the dynamic evolution of relevant variables over the next 40 years. These parameters include the electricity consumption, carbon pricing, energy price, and rate of decline in emerging energy technology costs. Given that a single scenario cannot sufficiently account for future uncertainties, a multi-scenario analysis approach is essential to transparently and quantitatively represent different future possibilities. To address operational uncertainties, sampling methods such as the Monte Carlo method are employed to generate stochastic representations of operating conditions and disturbances, thereby constructing uncertain scenarios. This process transforms a highly stochastic problem into a set of tractable deterministic problems. Each scenario is then simulated to quantify the associated operational risks.

Regarding optimization methods, the risk-optimal pathway is identified by evaluating candidate pathways across all scenarios. During the operational optimization process, the demand of the power system for stability control devices (e.g., synchronous condensers, static var compensators, static synchronous compensators, and series compensation) and flexible regulation resources (e.g., energy storage and transmission networks) are assessed to support proactive planning. This approach mitigates operational constraints on the transition pathway. Ultimately, solutions derived from individual deterministic scenarios are aggregated into pre-decision strategies, enhancing the robustness and resilience of decision-making under uncertainty.

#### IV. MATHEMATICAL MODEL OF CO-OPTIMIZATION OF CARBON REDUCTION AND CARBON SEQUESTRATION IN POWER SECTOR

##### A. Objective Function

For the decision-making of low-carbon development strategy at the national and regional levels, the objective function is defined as minimizing the cumulative economic cost associated with power supply and CCS deployment over the course of the transition period, that is,

$$\min C = \sum_{t \in T} (C_t^R + C_t^S) \quad (1)$$

where  $t$  is the index of the simulation time step;  $C_t^R$  is the economic cost of electricity supply at time step  $t$ , defined as the carbon reduction cost in this study;  $C_t^S$  is the economic cost of the CCS system configuration at time step  $t$ , defined as the carbon sequestration cost in this study; and  $T$  is the time horizon of the study period.

The economic costs associated with carbon reduction in the power sector mainly include the power system construction and operation costs required to ensure reliable supply and meet decarbonization goals, as well as the external costs arising from these activities. These costs can be expressed as:

$$C_t^R = C_t^P + C_t^G + C_t^{R,E} \quad (2)$$

where  $C_t^P$  is the plant-level cost at time step  $t$ ;  $C_t^G$  is the grid-level cost at time step  $t$ , including grid connection costs for new capacity, grid reinforcement and expansion costs, balancing costs, and reserve costs; and  $C_t^{R,E}$  is the externality cost of power generation at time step  $t$ .

The plant-level cost can be expressed as:

$$C_t^P = \sum_{i \in I_t} (C_{i,t}^c + C_{i,t}^m + C_{i,t}^f) \quad (3)$$

where  $i$  is the index of the power generation object;  $I_t$  is the set of power generation objects operating at time step  $t$ ;  $C_{i,t}^c$  is the depreciated construction cost of power generation object  $i$  at time step  $t$ ;  $C_{i,t}^m$  is the maintenance cost of power generation object  $i$  at time step  $t$ ; and  $C_{i,t}^f$  is the fuel cost of power generation object  $i$  at time step  $t$ .

The construction cost, maintenance cost, and fuel cost of power generation object  $i$  can be expressed as:

$$C_{i,t}^c = \frac{P_{i,t} A_i^c l_t}{l_i} \quad (4)$$

$$C_{i,t}^m = P_{i,t} H_{i,t} A_{i,t}^m \quad (5)$$

$$C_{i,t}^f = P_{i,t} H_{i,t} \gamma_{i,t} A_{i,t}^f \quad (6)$$

where  $P_{i,t}$  is the installed capacity of power generation object  $i$  at time step  $t$ ;  $A_i^c$  is the unit capital cost of power generation object  $i$ ;  $l_t$  is the time step in the simulation;  $l_i$  is the designed lifespan of power generation object  $i$ ;  $H_{i,t}$  is the utilization time of power generation object  $i$  at time step  $t$ ;  $A_{i,t}^m$  is the maintenance cost per unit of electricity generation for power generation object  $i$  at time step  $t$ ;  $\gamma_{i,t}$  is the average fuel consumption per unit of electricity generation for power generation object  $i$  at time step  $t$ ; and  $A_{i,t}^f$  is the fuel cost of power generation object  $i$  at time step  $t$ . For non-fossil power generation objects,  $H_{i,t}$  is a typical value based on the clean energy priority dispatch principle, while for fossil power generation objects, it is the output result from energy balance analyses.

The externality cost of power generation arises from social and environmental impacts like air pollution, climate change, and resource depletion associated with electricity production. Neglecting these externalities in pathway assessments may foster the growth of energy-intensive and high-emission industries. This study focuses on two negative external costs, i.e., the social cost of carbon and the scarcity cost of fossil resources. The externality cost of power generation is expressed as:

$$C_t^{R,E} = C_t^{R,c} + C_t^{R,r} \quad (7)$$

where  $C_t^{R,c}$  is the social cost of carbon due to power generation at time step  $t$ ; and  $C_t^{R,r}$  is the scarcity cost of fossil resources consumed by thermal power plants at time step  $t$ .

The social cost of carbon includes both the direct economic damages and the indirect damages to the environment, ecosystems, and human health caused by carbon dioxide emissions from electricity generation. It can be expressed as:

$$C_t^{R,c} = A_t^{\text{SCC}} \sum_{i \in I_t} P_{i,t} H_{i,t} \gamma_{i,t} \varphi_{i,t} \quad (8)$$

where  $\varphi_{i,t}$  is the fuel emission factor for power generation object  $i$  at time step  $t$ , which primarily depends on the type

of fuel; and  $A_t^{\text{SCC}}$  is the social marginal cost associated with an additional unit of carbon emissions at time step  $t$ .

Unlike renewable energy, fossil fuels are exhaustible. Since market prices don't account for the intergenerational externalities of fossil fuels, they don't fully reflect their true scarcity. Thus, it is important to include this scarcity in the economic cost of power supply. The scarcity cost of fossil resources can be expressed as:

$$C_t^{\text{R,r}} = A_t^{\text{r}} \sum_{i \in I_t} P_{i,t} H_{i,t} \gamma_{i,t} \quad (9)$$

where  $A_t^{\text{r}}$  is the scarcity cost associated with an additional unit of fossil fuels at time step  $t$ .

The economic costs associated with carbon sequestration in the power sector encompass the comprehensive costs of capturing CO<sub>2</sub> emissions from thermal power plants or free CO<sub>2</sub> in the atmosphere and transporting it to suitable locations for permanent storage. It assumes that the installed capacity of the CCS facilities for these power plants is adequate to meet total carbon capture requirements. Additionally, external costs incurred during this process are also considered. These costs can be expressed as:

$$C_t^{\text{S}} = C_t^{\text{CCS,T}} + C_t^{\text{CCS,A}} + C_t^{\text{S,E}} \quad (10)$$

where  $C_t^{\text{CCS,T}}$  is the comprehensive cost associated with CCS in thermal power generation at time step  $t$ ;  $C_t^{\text{CCS,A}}$  is the comprehensive cost of direct air carbon capture and storage (DACCS) at time step  $t$ ; and  $C_t^{\text{S,E}}$  is the externality cost of carbon sequestration in the power sector at time step  $t$ .

The comprehensive cost associated with CCS in thermal power generation can be expressed as:

$$C_t^{\text{CCS,T}} = A_{i,t}^{\text{CCS}} \sum_{i \in I_t} P_{i,t} H_{i,t} \gamma_{i,t} \varphi_{i,t} [\psi_{i,t} (1 + \Delta \gamma_{i,t}) - \Delta \gamma_{i,t}] \quad (11)$$

where  $\psi_{i,t}$  is the carbon capture rate of power generation object  $i$  at time step  $t$ ;  $\Delta \gamma_{i,t}$  is the percentage increase in fuel consumption per unit of electricity generated for power generation object  $i$  after the CCS retrofit at time step  $t$ ; and  $A_{i,t}^{\text{CCS}}$  is the cost per unit of net CO<sub>2</sub> captured and stored for power generation object  $i$  at time step  $t$ , which includes the depreciated costs of CCS equipment as well as operation costs.

The externality cost of carbon sequestration in the power sector includes the scarcity costs of fossil fuel consumption arising from the increased energy demand during the CCS process, as well as the social benefits gained from enhanced carbon sequestration, expressed as:

$$C_t^{\text{S,E}} = C_t^{\text{S,c}} + C_t^{\text{S,r}} \quad (12)$$

$$C_t^{\text{S,c}} = -A_t^{\text{SCC}} \sum_{i \in I_t} P_{i,t} H_{i,t} \gamma_{i,t} \varphi_{i,t} [\psi_{i,t} (1 + \Delta \gamma_{i,t}) - \Delta \gamma_{i,t}] \quad (13)$$

$$C_t^{\text{S,r}} = A_t^{\text{r}} \sum_{i \in I_t} P_{i,t} H_{i,t} \gamma_{i,t} \Delta \gamma_{i,t} \quad (14)$$

where  $C_t^{\text{S,r}}$  is the scarcity cost of fossil energy consumption resulting from CCS in the power sector at time step  $t$ ; and  $C_t^{\text{S,c}}$  is the social cost of carbon associated with CCS in the power sector at time step  $t$ . Since carbon sequestration positively impacts atmospheric greenhouse gas concentrations, its social cost of carbon is negative, reflecting external benefits.

## B. Constraints

The optimization of pathways for carbon reduction and carbon sequestration in the power sector involves security, technical, economic, and environmental constraints.

### 1) Security Constraints

The balance between power supply and demand is the primary constraint in power planning.

1) The total output power of the power generation objects at each time step must not be less than the peak load demand at that time step, that is,

$$\sum_{i \in I_t} P_{i,t} \lambda_{i,t} + \sum_{j \in J_t} P_{j,t} \lambda_{j,t} \geq L_t^{\text{max}} (1 + R_t) \quad t \in T \quad (15)$$

where  $\lambda_{i,t}$  is the output power coefficient of power generation object  $i$  at time step  $t$ , denoting the ratio of firm power at peak load to installed capacity;  $j$  is the serial number of an energy storage object;  $P_{j,t}$  is the installed capacity of energy storage object  $j$  at time step  $t$ ;  $J_t$  is the set of energy storage objects (including pumped hydro energy storage) operating at time step  $t$ ;  $\lambda_{j,t}$  is the output power coefficient of the energy storage object  $j$  at time step  $t$ , typically set to be 100%;  $L_t^{\text{max}}$  is the maximum power system load at time step  $t$ ; and  $R_t$  is the power reserve ratio at time step  $t$ .

2) The electricity production capacity of the power system at each time step must not be less than the electricity demand at that time step, that is,

$$\sum_{i \in I_t} P_{i,t} H_{rd,i} (1 - \eta_{i,t}) \geq \frac{Q_t}{1 - \varepsilon_t} \quad t \in T \quad (16)$$

where  $H_{rd,i}$  is the rated utilization time of power generation object  $i$ ;  $\eta_{i,t}$  is the auxiliary power consumption rate of power generation object  $i$  at time step  $t$ ;  $Q_t$  is the electricity demand at time step  $t$ ; and  $\varepsilon_t$  is the line loss rate in power grids at time step  $t$ .

### 2) Technical Constraints

Carbon reduction and carbon sequestration in the power sector require the support of two types of technologies: one is non-fossil power generation technology, which achieves near-zero emissions by replacing conventional fossil fuel-based power generation; the other is CCS technology, which converts carbon emissions from electricity production into sequestered carbon.

1) The capacity of each type of newly constructed power generation objects at time step  $t$  is limited by the construction capability, that is,

$$\sum_{i \in I_t^{\text{NC}} \cap I_{\text{GT}}} P_{i,t} \leq P_{\text{GT},t}^{\text{NC,max}} \quad t \in T \quad (17)$$

where  $I_t^{\text{NC}}$  is the set of newly constructed power generation objects at time step  $t$ ;  $I_{\text{GT}}$  is the set of power generation objects of type GT (GT includes any type of power generation such as coal-fired, gas-fired, oil-fired, wind, and PV); and  $P_{\text{GT},t}^{\text{NC,max}}$  is the maximum capacity of newly constructed power generation objects of type GT at time step  $t$ .

2) The total exploitable non-fossil energy is constrained by resource endowments, that is,

$$\sum_{i \in I_t \cap I_{\text{GT}}} P_{i,t} \leq P_{\text{GT}}^{\text{max}} \quad t \in T \quad (18)$$

where  $P_{\text{GT}}^{\text{max}}$  is the maximum exploitable energy potential of

type GT.

3) The retrofit of thermal power generation objects with CCS at each time step is constrained by the implementation capacity, that is,

$$\sum_{i \in I_t^{\text{NR}}} P_{i,t} \leq P_t^{\text{NR,max}} \quad t \in T \quad (19)$$

where  $I_t^{\text{NR}}$  is the set of power generation objects newly retrofitted with CCS at time step  $t$ ; and  $P_t^{\text{NR,max}}$  is the maximum CCS retrofit implementation capacity at time step  $t$ .

4) The upper limit on the number of CCS facilities implemented on power generation objects is constrained by retrofitted conditions and source-sink matching requirements, that is,

$$\sum_{i \in I_t, t \in I_R} P_{i,t} \leq P_t^{\text{R,max}} \quad t \in T \quad (20)$$

where  $I_R$  is the set of power generation objects with CCS; and  $P_t^{\text{R,max}}$  is the maximum power capacity available for implementing CCS at time step  $t$ .

### 3) Economic Constraints

Investment in carbon reduction and carbon sequestration in the power sector is limited by a total investment cap, that is,

$$C_t^{\text{P}} + C_t^{\text{G}} + C_t^{\text{CCS,T}} + C_t^{\text{CCS,A}} \leq C_t^{\text{max}} \quad t \in T \quad (21)$$

where  $C_t^{\text{max}}$  is the upper limit of the total investment at time step  $t$ .

### 4) Environmental Constraints

1) The emission peaking time should occur at or before the target peaking time, that is,

$$T_p^{\text{P}} - T_p^{\text{I}} \leq 0 \quad (22)$$

where  $T_p^{\text{P}}$  is the target peaking time; and  $T_p^{\text{I}}$  is the peaking time of CO<sub>2</sub> emissions in pathway planning.

2) Carbon sequestration should be at least equal to or greater than carbon emissions in the year specified by the carbon neutrality target, that is,

$$S_N^{\text{P}} - E_N^{\text{P}} \geq 0 \quad (23)$$

where  $S_N^{\text{P}}$  is the carbon sequestration in carbon neutrality target year within the pathway planning; and  $E_N^{\text{P}}$  is the carbon emission in carbon neutrality target year within the pathway planning.

## V. CASE STUDY ON CO-OPTIMIZATION OF CARBON REDUCTION AND CARBON SEQUESTRATION IN POWER SECTOR

This study explores the transition of the power sector in China toward carbon peaking and carbon neutrality goals. It designs several candidate pathways aligned with these goals and identifies the optimal pathway for carbon reduction and carbon sequestration through a quantitative assessment of costs, including the electricity infrastructure and the social cost of carbon.

### A. Scenario Parameter Settings and Pathway Design

The scenario settings in this study follow those in [14]. Therefore, the focus is primarily on the pathway design.

Numerous potential low-carbon development goals and pathways exist within the optimization space. Given the di-

versity of endpoints and carbon trajectories, several representative terminal carbon states are defined within the critical neutrality domain. Evolutionary pathways from the initial carbon state to each terminal carbon state are then clustered into several carbon trajectories, generating nine candidate pathways.

The variation in terminal carbon states reflects differentiated targets for carbon reduction and carbon sequestration, while differing carbon trajectories indicate distinct timelines for achieving these goals. The pathway design adheres to these principles.

1) The endpoints of the nine candidate carbon trajectories fall within the critical neutrality domain. A binary array is employed to denote the terminal carbon state, with two elements representing carbon emission and sequestration in the target year for carbon neutrality. For example,  $[2.8 \times 10^9, 2.8 \times 10^9]\text{t}$  represents the carbon emission and carbon sequestration in the year of carbon neutrality, both being 2.8 billion tons.

2) The trajectories are identical before the carbon peaking. Afterward, the carbon reduction pathways diverge into three forms: early-acceleration, uniform-speed, and late-acceleration, corresponding to aggressive, steady, and conservative emission reduction strategies, respectively. The uniform-speed pathway serves as a benchmark, while early- and late-acceleration pathways reflect front-loaded and back-loaded reductions, respectively. All pathways share a common pathway for phasing out coal-fired power generation, differing only in the utilization rates of coal-fired power generators, which subsequently impacts alternative energy pathways.

3) Assuming a fixed low-carbon pathway for non-electricity industries, society-wide carbon peaking and carbon neutrality are achieved through targeted efforts within the power sector.

### B. Comparative Analysis of Multi-pathways

This subsection examines carbon reduction and carbon sequestration pathways in the power sector with similar carbon trajectories but different terminal carbon states, as well as those with varying shapes converging on the same terminal carbon state. The analysis highlights the impact of carbon trajectory design on long-term power supply and carbon capture configurations.

#### 1) Similar Carbon Trajectories with Varying Terminal Carbon States

This study focuses on early-acceleration pathways with terminal carbon states of  $[2.8 \times 10^9, 2.8 \times 10^9]\text{t}$ ,  $[2.6 \times 10^9, 2.6 \times 10^9]\text{t}$ , and  $[2.4 \times 10^9, 2.4 \times 10^9]\text{t}$ , comparing their differences in power sector carbon emission, installed capacity, and CCS capacity, as shown in Fig. 2.

The three pathways have different terminal carbon states but similar carbon trajectories. In all three early-acceleration pathways, a consistent trend is observed, with rapid changes in power sector carbon emissions during the early transition stage, followed by stabilization in the later stage.

For carbon reduction, after excluding emissions from non-electricity sectors, the power sector carbon emissions under terminal carbon states of  $[2.8 \times 10^9, 2.8 \times 10^9]\text{t}$ ,  $[2.6 \times 10^9, 2.6 \times$

$10^9$ t, and  $[2.4 \times 10^9, 2.4 \times 10^9]$ t are expected to be  $7.3 \times 10^8$ ,  $5.3 \times 10^8$ , and  $3.3 \times 10^8$  t, respectively, in the carbon neutrality year. Coal-fired power plants shift more generation to renew-

ables, reducing overall carbon emissions. By 2060, wind and PV capacities in the three pathways will reach 6.24, 6.45, and 6.65 TW, respectively.

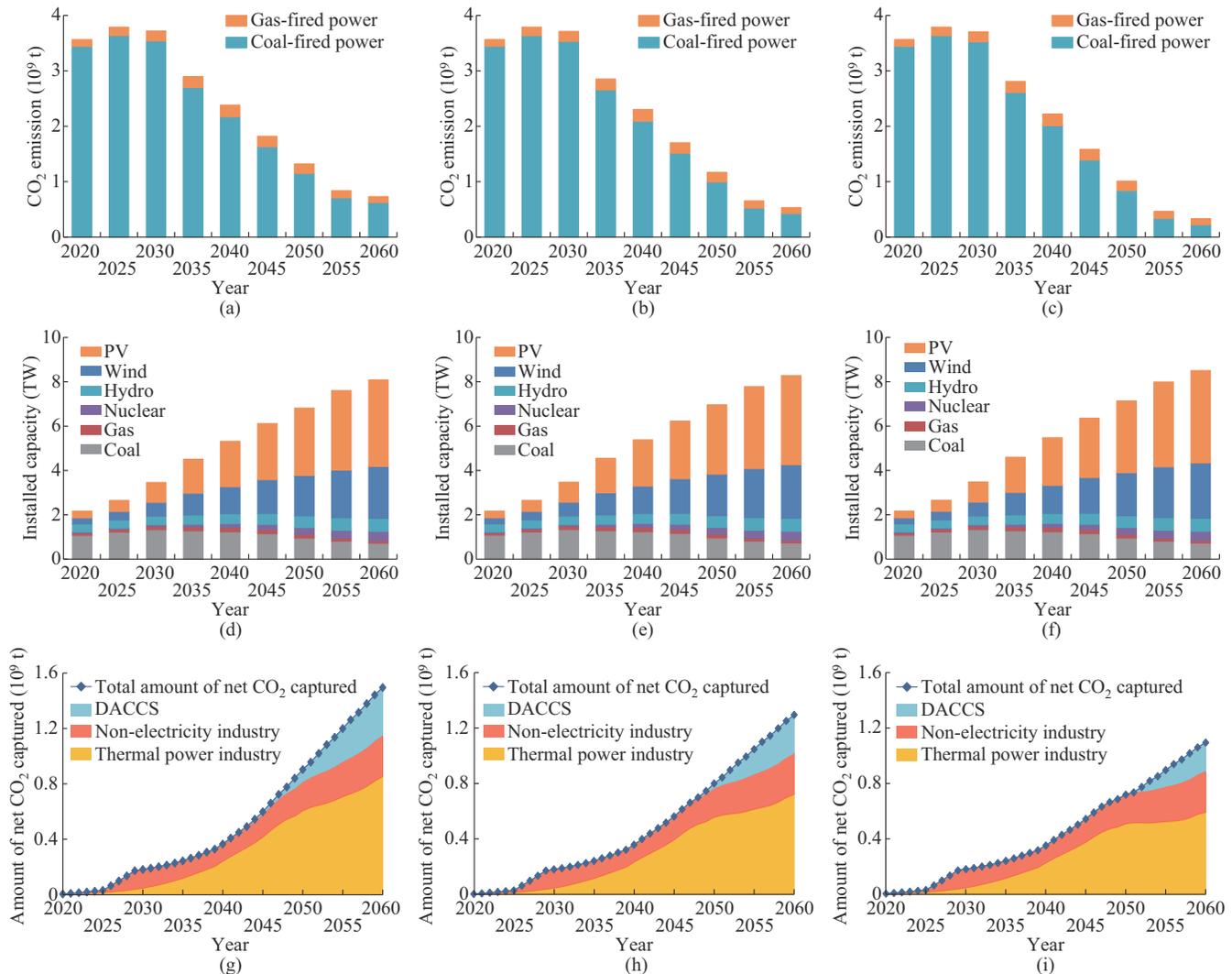


Fig. 2. Pathways under similar carbon trajectories with different terminal carbon states. (a) Power sector carbon emissions with a terminal carbon state of  $[2.8 \times 10^9, 2.8 \times 10^9]$ t. (b) Power sector carbon emissions with a terminal carbon state of  $[2.6 \times 10^9, 2.6 \times 10^9]$ t. (c) Power sector carbon emissions with a terminal carbon state of  $[2.4 \times 10^9, 2.4 \times 10^9]$ t. (d) Installed capacity with a terminal state of  $[2.8 \times 10^9, 2.8 \times 10^9]$ t. (e) Installed capacity with a terminal carbon state of  $[2.6 \times 10^9, 2.6 \times 10^9]$ t. (f) Installed capacity with a terminal carbon state of  $[2.4 \times 10^9, 2.4 \times 10^9]$ t. (g) Amount of net  $\text{CO}_2$  captured with a terminal carbon state of  $[2.8 \times 10^9, 2.8 \times 10^9]$ t. (h) Amount of net  $\text{CO}_2$  captured with a terminal carbon state of  $[2.6 \times 10^9, 2.6 \times 10^9]$ t. (i) Amount of net  $\text{CO}_2$  captured with a terminal carbon state of  $[2.4 \times 10^9, 2.4 \times 10^9]$ t.

For carbon sequestration,  $\text{CO}_2$  concentration significantly affects energy consumption and capture costs. Coal-fired power plants, with higher  $\text{CO}_2$  concentration in flue gas, make  $\text{CO}_2$  capture economically viable, thus becoming a preferred option. Direct air capture, while not constrained by emission sources or location, is costly and energy-intensive, acting as a fallback for residual sequestration needs. The more aggressive the carbon reduction target, the lower the demand for carbon sequestration, and fewer suitable capture points remain. For pathways under the terminal carbon states of  $[2.8 \times 10^9, 2.8 \times 10^9]$ t,  $[2.6 \times 10^9, 2.6 \times 10^9]$ t, and  $[2.4 \times 10^9, 2.4 \times 10^9]$ t, the amounts of  $\text{CO}_2$  captured from coal-fired power plants in the carbon neutrality year will be  $4.1 \times 10^8$ ,  $2.8 \times 10^8$ , and  $1.5 \times 10^8$  t, respectively. To meet carbon sequestration tar-

gets, the required amounts of direct air capture in the same year are  $3.4 \times 10^8$ ,  $2.7 \times 10^8$ , and  $2.0 \times 10^8$  t of  $\text{CO}_2$ , respectively.

The pathway evaluation results under the three terminal carbon states of  $[2.8 \times 10^9, 2.8 \times 10^9]$ t,  $[2.6 \times 10^9, 2.6 \times 10^9]$ t, and  $[2.4 \times 10^9, 2.4 \times 10^9]$ t are compared in Fig. 3, leading to the following conclusions. In Fig. 3, tce denotes the ton of standard coal equivalent.

1) From the perspective of power supply costs, the tightening of the carbon emission budget reduces the share of coal-fired power generation in the total power mix, leading to lower coal-fired power generation costs, particularly in fuel expenses. Simultaneously, rising demand for renewable energy has stimulated investment growth in the power sector. Despite variations in carbon reduction targets, the cumulative

plant-level costs from 2020 to 2060 remain relatively consistent, amounting to  $1.078 \times 10^{14}$ ,  $1.077 \times 10^{14}$ , and  $1.076 \times 10^{14}$  CNY, respectively. However, the increasing share of renewable energy has driven up grid infrastructure construction and operation costs, with cumulative grid-level costs reach-

ing  $5.45 \times 10^{13}$ ,  $5.65 \times 10^{13}$ , and  $5.86 \times 10^{13}$  CNY. In summary, while plant-level costs remain stable due to advancements in renewable technologies, the growth in grid-level costs will exceed plant-level savings, resulting in an overall rise in total power supply costs.

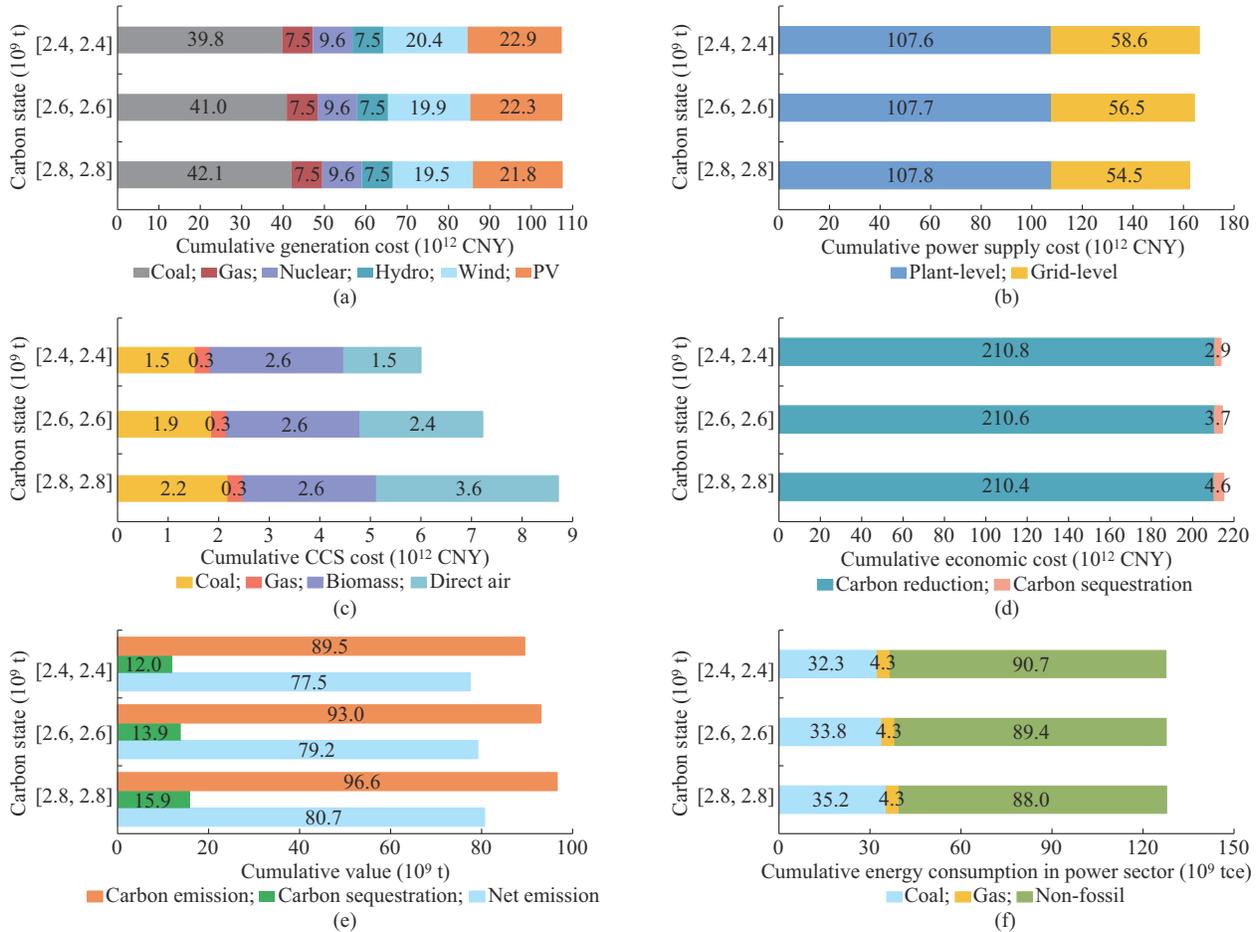


Fig. 3. Pathway evaluation results under three terminal carbon states. (a) Cumulative generation costs. (b) Cumulative power supply costs. (c) Cumulative CCS costs in power sector. (d) Cumulative economic costs of carbon reduction and carbon sequestration. (e) Cumulative carbon emission, cumulative carbon sequestration, and cumulative net emission. (f) Cumulative energy consumption in power sector.

2) From the perspective of cumulative CCS costs in the power sector, higher carbon reduction targets correspondingly diminish the need for carbon sequestration. Priority should be given to CCS facilities integrated with coal-fired power plants, while the residual carbon sequestration demand can be addressed through DACCS. For the pathways with terminal carbon states of  $[2.8 \times 10^9, 2.8 \times 10^9]$ t,  $[2.6 \times 10^9, 2.6 \times 10^9]$ t, and  $[2.4 \times 10^9, 2.4 \times 10^9]$ t, the cumulative CCS costs for coal-fired power plants are  $2.2 \times 10^{12}$ ,  $1.9 \times 10^{12}$ , and  $1.5 \times 10^{12}$  CNY, respectively. The corresponding costs of DACCS are  $3.6 \times 10^{12}$ ,  $2.4 \times 10^{12}$ , and  $1.5 \times 10^{12}$  CNY, respectively. Consequently, cumulative CCS costs in the power sector amount to  $8.7 \times 10^{12}$ ,  $7.2 \times 10^{12}$ , and  $6.0 \times 10^{12}$  CNY, respectively. The analysis shows that reducing carbon sequestration targets significantly lowers CCS-related costs.

3) From the perspective of the externality costs, lowering target values for carbon emission and carbon sequestration in the carbon neutrality year reduces cumulative carbon emission, carbon sequestration, net emission, and fossil energy

consumption within the power sector.

### 2) Different Carbon Trajectories with Same Terminal Carbon State

This study examines the variations among the early-acceleration, uniform-speed, and late-acceleration pathways with a terminal carbon state of  $[2.6 \times 10^9, 2.6 \times 10^9]$ t. These pathways are compared in terms of energy-related carbon emissions, carbon emissions from the power sector, and CCS capacity of coal-fired power plants. The comparison is illustrated in Fig. 4.

The three pathways converge at the same terminal carbon state, leading to identical configurations for power supply and carbon capture by the carbon neutrality year. The difference lies solely in the trajectories taken to achieve this terminal carbon state.

In terms of carbon reduction, the varying temporal allocation of carbon reduction tasks creates distinct patterns in key indicators such as power sector carbon emission, fossil energy consumption, and average utilization time of thermal

power equipment across the early-acceleration, uniform-speed, and late-acceleration pathways. The early-acceleration pathway exhibits a concave trajectory, the uniform-speed pathway approximates a linear trend, and the late-acceleration pathway displays a convex shape. In the early transition stages, the early-acceleration pathway faces significant pressure regarding new energy infrastructure, as coal-fired power generation transitions from being the dominant source of

electricity to serving as a crucial provider of reliable power and load balancing. The average utilization time of coal-fired power generation declines from 4213 hours in 2020 to 966 hours by 2055, stabilizing thereafter. In contrast, the late-acceleration pathway maintains high utilization time of coal-fired power generation until 2035, followed by a rapid decline.

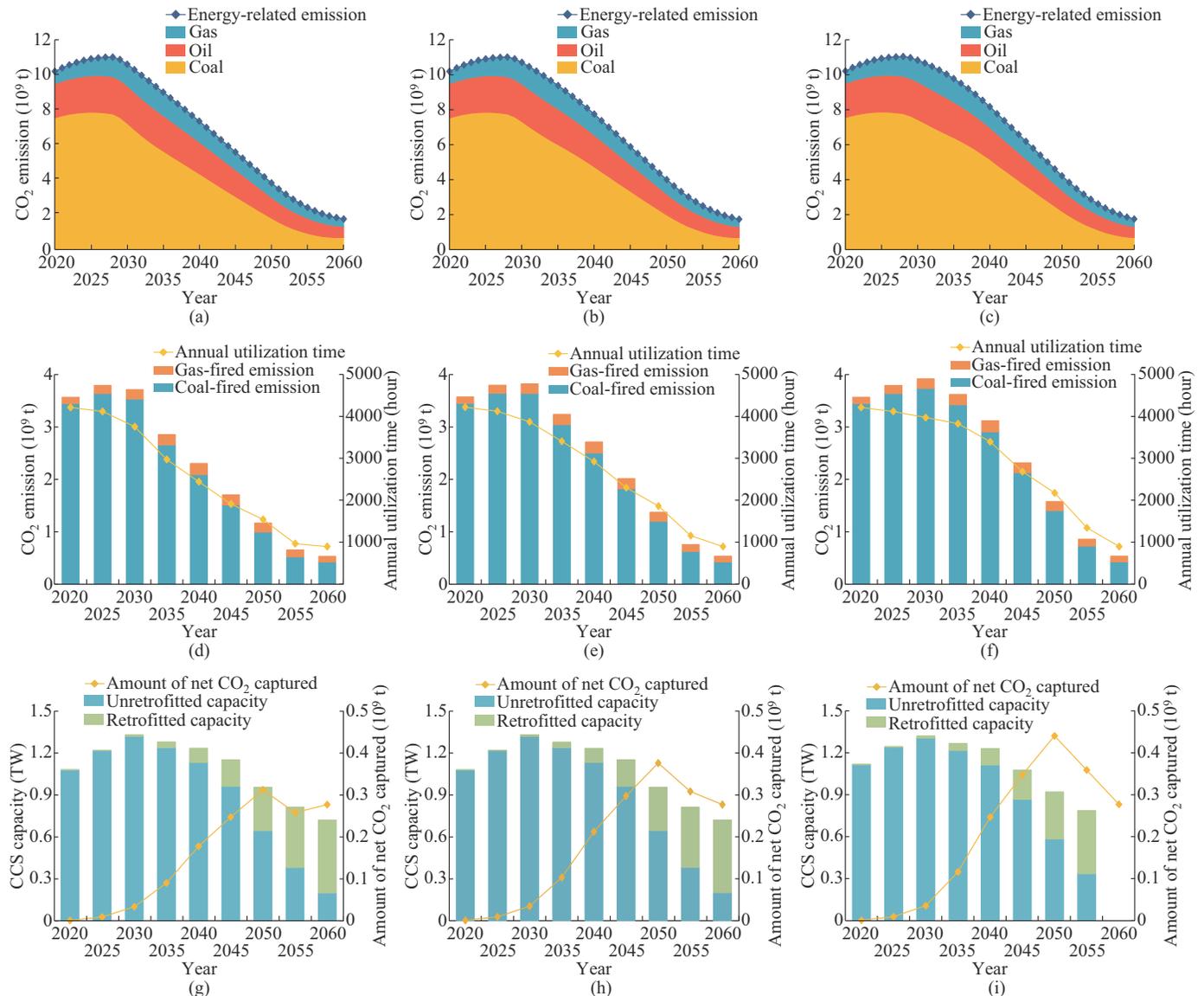


Fig. 4. Pathways under different carbon trajectories with same terminal carbon state. (a) Energy-related carbon emissions in early-acceleration pathway. (b) Energy-related carbon emissions in uniform-speed pathway. (c) Energy-related carbon emissions in late-acceleration pathway. (d) Power sector carbon emissions in early-acceleration pathway. (e) Power sector carbon emissions in uniform-speed pathway. (f) Power sector carbon emissions in late-acceleration pathway. (g) CCS capacity and amount of net  $\text{CO}_2$  captured of coal-fired power plants in early-acceleration pathway. (h) CCS capacity and amount of net  $\text{CO}_2$  captured of coal-fired power plants in uniform-speed pathway. (i) CCS capacity and amount of net  $\text{CO}_2$  captured of coal-fired power plants in late-acceleration pathway.

In terms of carbon sequestration, the early-acceleration pathway schedules carbon reduction tasks earlier in the timeline, leading to a decrease in the number of emission sources available for carbon capture during the transition process. Although the timeline for retrofitting coal-fired power plants with CCS technology is consistent across the pathways, dif-

ferences in the utilization rates of coal-fired power generation lead to varying amounts of carbon captured. In the early transition stages, as retrofitting accelerates, annual amount of carbon captured increases rapidly. However, in later stages, as the utilization rate of coal-fired power generation declines, the growth rate of annual amount of carbon captured

slows down and may even decrease. Across all three pathways, the annual amount of carbon captured from coal-fired power generation is non-monotonic, peaking in 2055 at  $3.1 \times 10^9$ ,  $3.8 \times 10^9$ , and  $4.4 \times 10^9$  t of  $\text{CO}_2$  for the early-acceleration, uniform-speed, and late-acceleration pathways, respectively,

before declining to  $2.8 \times 10^9$  t of  $\text{CO}_2$  by 2060.

By comparing the early-acceleration, uniform-speed, and late-acceleration pathways with a terminal carbon state of  $[2.6 \times 10^9, 2.6 \times 10^9]$ t, as shown in Fig. 5, the following conclusions are drawn.

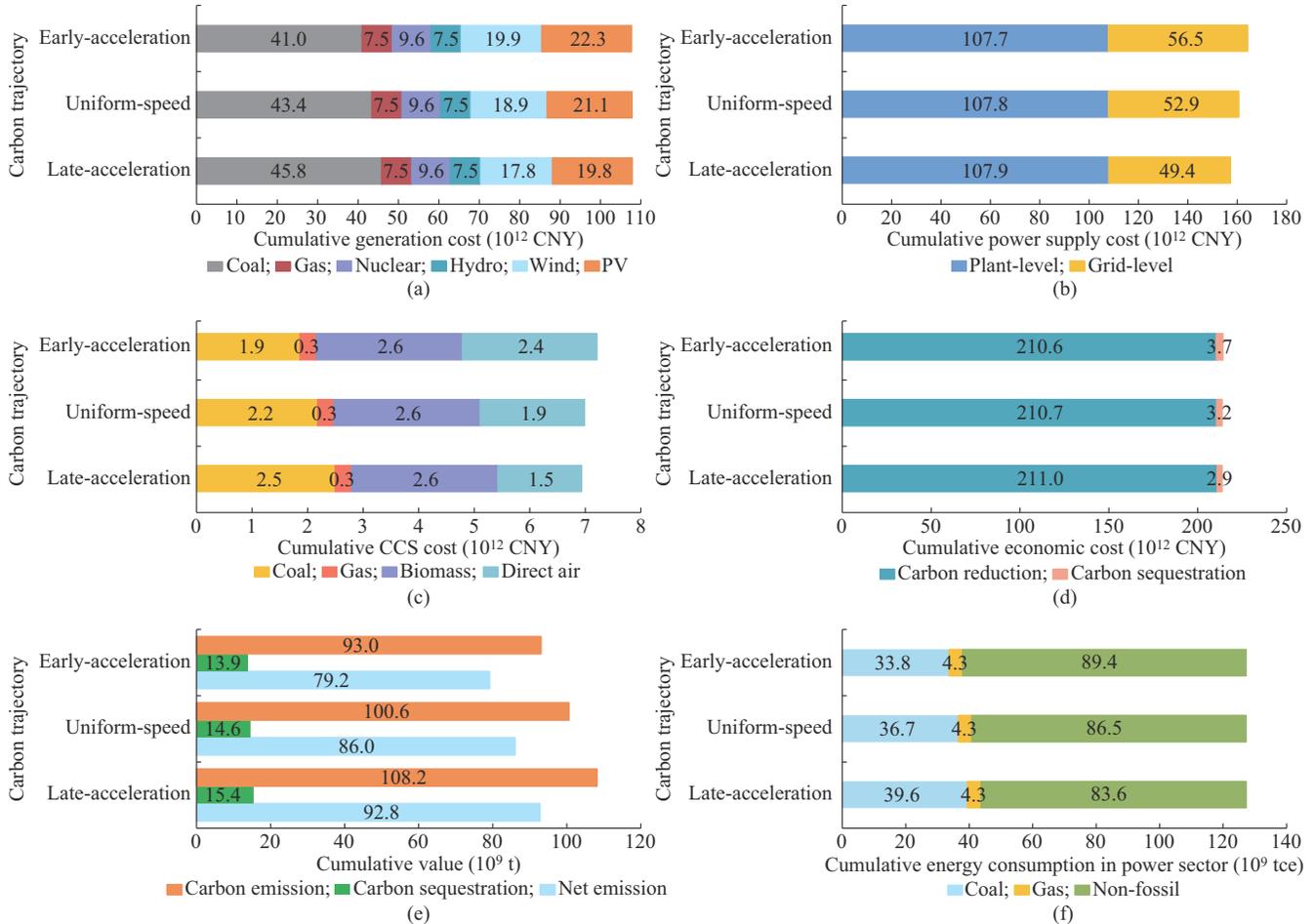


Fig. 5. Pathway evaluation results under three carbon trajectories. (a) Cumulative generation costs. (b) Cumulative power supply costs. (c) Cumulative CCS costs in power sector. (d) Cumulative economic costs of carbon reduction and carbon sequestration. (e) Cumulative carbon emission, cumulative carbon sequestration, and cumulative net emission. (f) Cumulative energy consumption in power sector.

1) From the perspective of power supply costs, the late-acceleration pathway accelerates the development of renewable energy, hastening the transition of coal-fired power generation from a dominant to a foundational source. Throughout the transition period, the growth in renewable energy investment is accompanied by a corresponding decrease in the costs associated with coal-fired power generation. The cumulative generation costs for the early-acceleration, uniform-speed, and late-acceleration pathways are  $9.79 \times 10^{13}$ ,  $9.80 \times 10^{13}$ , and  $9.81 \times 10^{13}$  CNY, respectively, indicating a more aggressive carbon reduction pathway does not raise plant-level costs but rather lowers them. However, the grid-level costs increase significantly to balance the intermittent output of renewable energy. Since the rise in grid-level costs surpasses the decline in plant-level costs, a more aggressive carbon reduction pathway results in higher cumulative power supply costs, totaling  $1.643 \times 10^{14}$ ,  $1.607 \times 10^{14}$ , and  $1.573 \times 10^{14}$  CNY

for the early-acceleration, uniform-speed, and late-acceleration pathways, respectively.

2) From the perspective of the cumulative CCS costs in the power sector, a more aggressive carbon reduction pathway results in fewer emission sources available for carbon capture during the transition, thereby increasing the reliance on DACCS as a fallback technology. This leads to higher cumulative CCS costs in the power sector. For the early-acceleration, uniform-speed, and late-acceleration pathways with a terminal carbon state of  $[2.6 \times 10^9, 2.6 \times 10^9]$ t, the cumulative CCS costs in the power sector are  $7.2 \times 10^{12}$ ,  $7.0 \times 10^{12}$ , and  $6.9 \times 10^{12}$  CNY, respectively.

3) From the perspective of externality costs, the early-acceleration pathway advances carbon reduction efforts, resulting in lower cumulative carbon emission, carbon sequestration, net emission, and fossil energy consumption compared with those of the other two pathways.

### C. Discussion of Pathway Optimization Strategies

Table I shows the cumulative plant-level and grid-level costs of the nine candidate pathways.

Based on the simulation results of plant-level and grid-level costs, the following conclusions can be drawn.

1) Setting ambitious carbon reduction targets and pathways can result in fuel cost savings that offset new energy investments, thereby reducing overall plant-level costs. However, the power grid will require substantial infrastructure up-

grades to handle a high proportion of renewable energy, resulting in increased grid-level costs.

2) While cumulative plant-level costs exceed grid-level costs across various pathways, they tend to converge, with a maximum difference of only  $4 \times 10^{11}$  CNY. In contrast, grid-level costs show considerable divergence, with a maximum difference of  $1.1 \times 10^{13}$  CNY.

Table II presents the cumulative carbon reduction costs and cumulative carbon sequestration costs of the nine candidate pathways.

TABLE I  
CUMULATIVE PLANT-LEVEL AND GRID-LEVEL COSTS OF NINE CANDIDATE PATHWAYS

Carbon trajectory	Cumulative plant-level cost ( $10^{14}$ CNY)			Cumulative grid-level cost ( $10^{13}$ CNY)		
	$[2.8 \times 10^9, 2.8 \times 10^9]$ t	$[2.6 \times 10^9, 2.6 \times 10^9]$ t	$[2.4 \times 10^9, 2.4 \times 10^9]$ t	$[2.8 \times 10^9, 2.8 \times 10^9]$ t	$[2.6 \times 10^9, 2.6 \times 10^9]$ t	$[2.4 \times 10^9, 2.4 \times 10^9]$ t
Early-acceleration	1.078	1.077	1.076	0.545	0.565	0.586
Uniform-speed	1.079	1.078	1.077	0.510	0.529	0.548
Late-acceleration	1.080	1.079	1.078	0.476	0.494	0.512

TABLE II  
CUMULATIVE CARBON REDUCTION COSTS AND CUMULATIVE CARBON SEQUESTRATION COSTS OF NINE CANDIDATE PATHWAYS

Carbon trajectory	Cumulative carbon reduction cost ( $10^{14}$ CNY)			Cumulative carbon sequestration cost ( $10^{13}$ CNY)		
	$[2.8 \times 10^9, 2.8 \times 10^9]$ t	$[2.6 \times 10^9, 2.6 \times 10^9]$ t	$[2.4 \times 10^9, 2.4 \times 10^9]$ t	$[2.8 \times 10^9, 2.8 \times 10^9]$ t	$[2.6 \times 10^9, 2.6 \times 10^9]$ t	$[2.4 \times 10^9, 2.4 \times 10^9]$ t
Early-acceleration	2.104	2.106	2.108	0.046	0.037	0.029
Uniform-speed	2.106	2.107	2.109	0.040	0.032	0.027
Late-acceleration	2.110	2.110	2.111	0.035	0.029	0.025

The analysis of the cumulative economic costs associated with power supply (i.e., carbon reduction costs) and CCS deployment (i.e., carbon sequestration costs) for the nine candidate pathways presented in Table II leads to the following conclusions.

1) The target value for carbon sequestration is the primary factor affecting cumulative carbon sequestration costs. Increasing this target value raises expenditures. A higher carbon emission target in the carbon neutrality year and a higher acceleration degree of the carbon reduction pathway both increase carbon reduction costs, mainly due to higher grid-level costs.

2) All nine candidate pathways achieve carbon neutrality by 2060. With a fixed net emission target, carbon reduction and carbon sequestration tasks exhibit an inverse relationship. Adopting more aggressive carbon reduction strategies reduces the need for carbon sequestration, indicating that while cumulative carbon reduction costs increase, cumulative carbon sequestration expenses can be reduced. The selection of the optimal transition pathway of the power sector should be based on the joint modeling of both carbon reduction and carbon sequestration technologies, along with a simulation of the overall trajectory. Optimizing isolated subsystems or adopting time-step-based optimization methods is inconsistent with the holistic approach required for system-wide optimization.

In conclusion, the pathway optimization involves adjusting the allocation of tasks between carbon reduction and carbon sequestration to minimize cumulative economic costs for achieving carbon neutrality. The cumulative economic

costs for each pathway, shown in Fig. 6, reveal that the uniform-speed pathway with a terminal carbon state of  $[2.4 \times 10^9, 2.4 \times 10^9]$ t demonstrates the most favorable performance according to the objective function. It is important to note that the optimization results are valid only within certain parameter thresholds, and exceeding these thresholds may alter the outcomes.

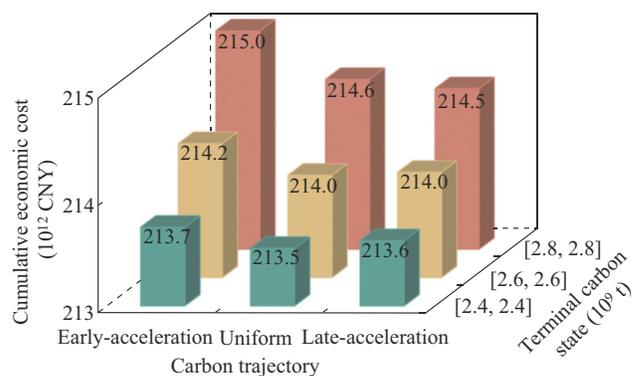


Fig. 6. Comparison of cumulative economic costs for each pathway.

To summarize, carbon reduction and carbon sequestration differ significantly across technological, economic, and environmental dimensions. Technologically, carbon reduction offers a wide range of mature and widely implemented options such as clean power generation. In contrast, carbon sequestration technologies are more limited, with the most promising option, CCS, still in the breakthrough phase, far from commercial operation and large-scale deployment. Economi-

cally, the carbon reduction is initially cost-effective, even negative, but becomes increasingly expensive in later stages. Conversely, carbon sequestration starts with higher costs but has substantial potential for cost reduction over time. Environmentally, carbon reduction targets CO<sub>2</sub> emissions at their source, with limited reduction potential within each sector. Carbon sequestration, on the other hand, captures and stores CO<sub>2</sub> already emitted, with technologies like direct air capture offering virtually limitless sequestration capacity by capturing CO<sub>2</sub> directly from the atmosphere. By fully exploiting the temporal and spatial complementarities between carbon reduction and carbon sequestration in technological, economic, and environmental aspects, the overall economic costs of achieving carbon neutrality can be minimized to the greatest extent possible.

## VI. CONCLUSION

In the context of carbon peaking and carbon neutrality transition, the challenges of carbon reduction and carbon sequestration in the power sector constitute a complex, evolving, large-scale system marked by uncertainty, non-linearity, and dynamic openness. This paper proposes an optimization framework for internal optimization and aggregated coordination of carbon reduction and carbon sequestration, supported by a tailored mathematical model and optimization method. The effectiveness of the proposed framework and method for co-optimizing carbon reduction and carbon sequestration is validated through simulation examples. The main conclusions are as follows.

1) The greater the acceleration degree of emission reduction is, the more aggressive the phase-out of coal-fired power generation becomes, accompanied by increased investment in renewable energy. Owing to the rapid advancements of renewable energy technologies, the savings in fuel costs are sufficient to offset the investment in renewable energy sources. However, in order to balance fluctuations in renewable energy generation, additional costs for the construction and operation of energy storage systems and other grid infrastructure are required, leading to a significant increase in overall power supply costs. In the accelerated reduction pathway, cumulative net emissions and fossil energy consumption are relatively low, demonstrating a higher level of environmental sustainability.

2) As the carbon emission budget for the carbon neutrality target year (2060 for China) tightens, traditional coal-fired power generation cedes an increasing share of generation capacity to renewable energy, thereby reducing overall carbon emissions. While plant-level costs converge across different terminal carbon states, notable disparities remain in grid-level costs, leading to an overall increase in power supply costs. The low utilization rate of coal-fired power plants limits the effectiveness of CCS systems. However, due to the substantial decrease in the demand for carbon sequestration required to achieve carbon neutrality, the overall cost of carbon sequestration declines. The key to optimizing the carbon neutrality pathway is to foster synergistic benefits between carbon reduction and carbon sequestration.

This study aims to optimize carbon reduction and carbon

sequestration measures, taking into account technological and resource availability, thereby providing a methodological reference for the optimization of carbon peaking and carbon neutrality transition pathways. The research highlights the synergistic effects of carbon reduction and carbon sequestration in advancing low-carbon development goals, providing theoretical insights and practical implications. Nonetheless, there are still some limitations that require further research in the following areas.

1) The carbon peaking and carbon neutrality transition represents a complex systemic undertaking involving multiple sectors and industries. The optimization objective for carbon reduction and carbon sequestration in the power sector is to support societal carbon neutrality at the lowest possible economic cost, rather than minimizing transition costs within the sector itself. This paper focuses on the power industry, assuming constant low-carbon pathways for non-electricity industries, and it does not account for cross-sectoral collaborative reduction.

2) While the optimization results of the proposed mathematical model offer valuable insights for decision-making on carbon reduction and carbon sequestration in the power sector, uncertainties, both external (e.g., carbon constraints and electricity demand) and internal (e.g., system structure and parameters) can significantly influence the outcomes. Consequently, it is essential to analyze the impact of parameter variations on optimization results and establish a mapping between uncertain parameters and pathway optimization outcomes.

3) This study does not model social elements within the CPSSE framework. Future research should focus on refining the design of precise policies and market mechanisms by employing a hybrid simulation method involving technology-economics-behavior-real person models to guide and incentivize the carbon reduction and carbon sequestration behaviors of market entities and facilitate the tracking of the optimal carbon peaking and carbon neutrality trajectories generated by the model.

## REFERENCES

- [1] J. Leng and Y. Xue, "Optimizing approaches for the development pathways of new power systems under the 'dual carbon' goals," *China Power Enterprise Management*, vol. 19, pp. 11-13, Jul. 2021.
- [2] Y. Shu, L. Zhang, Y. Zhang *et al.*, "Carbon peak and carbon neutrality path for China's power industry," *Chinese Journal of Engineering Science*, vol. 23, no. 6, p. 1-14, 2021.
- [3] X. Zhang, X. Huang, D. Zhang *et al.*, "Research on the pathway and policies for China's energy and economy transformation toward carbon neutrality," *Management World*, vol. 38, no. 1, pp. 35-66, Jan. 2022.
- [4] T. Qi, X. Zhang, and J. He, "Review of research on global energy-economic computable general equilibrium models," *China Population, Resources and Environment*, vol. 26, no. 8, pp. 42-48, Aug. 2016.
- [5] Y. Xue. (2022, Aug.). Integration of whole thinking and reductionism thinking: co-progress of basic research and applied research. [Online]. Available: [https://mp.weixin.qq.com/s/LBZZZiVjxkj\\_Fbesux4BA](https://mp.weixin.qq.com/s/LBZZZiVjxkj_Fbesux4BA)
- [6] Y. Wen, B. Cai, X. Yang *et al.*, "Quantitative analysis of China's low-carbon energy transition," *International Journal of Electrical Power & Energy Systems*, vol. 119, p. 105854, Jul. 2020.
- [7] B. Cai, Y. Xue, Y. Fan *et al.*, "Optimization on trans-regional electricity transmission scale of China's western renewable energy base: the case study of Qinghai Province," in *Proceedings of E3S Web of Conferences*, Guilin, China, Dec. 2019, pp. 1-9.
- [8] B. Cai, Y. Xue, X. Yang *et al.*, "Quantitative analysis of clean transi-

- tion strategy of traditional coal-dominated GenCos,” *Energy Procedia*, vol. 152, pp. 1021-1026, Oct. 2018.
- [9] X. Yang, B. Cai, and Y. Xue, “Review on optimization of nuclear power development: a cyber-physical-social system in energy perspective,” *Journal of Modern Power Systems and Clean Energy*, vol. 10, no. 3, pp. 547-561, May 2022.
- [10] X. Yang, Y. Xue, and B. Cai, “Pathway planning of nuclear power development incorporating assessment of nuclear event risk,” *Journal of Modern Power Systems and Clean Energy*, vol. 12, no. 2, pp. 500-513, Mar. 2024.
- [11] C. T. M. Clack, S. A. Qvist, J. Apt *et al.*, “Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar,” *Proceedings of the National Academy of Sciences of the United States of America*, vol. 114, no. 26, pp. 6722-6727, Jun. 2017.
- [12] N. A. Sepulveda, J. D. Jenkins, F. J. de Sisternes *et al.*, “The role of firm low-carbon electricity resources in deep decarbonization of power generation,” *Joule*, vol. 2, no. 11, pp. 2403-2420, Nov. 2018.
- [13] H. Sithole, T. T. Cockerill, K. J. Hughes *et al.*, “Developing an optimal electricity generation mix for the UK 2050 future,” *Energy*, vol. 100, pp. 363-373, Apr. 2016.
- [14] Y. Xue, M. Yang, B. Cai *et al.*, “Sand-table simulation for optimizing pathways of carbon emission reduction and carbon sink increment in electric power industry,” *Automation of Electric Power Systems*, vol. 48, no. 23, pp. 16-34, Dec. 2024.
- [15] Y. Zhang, Y. Xue, J. Huang *et al.* (2024, Sept.). Simulation-based validation of the equivalent coordination mechanism between carbon emission and carbon sink markets. *Automation of Electric Power Systems*. [Online]. Available: <http://kns.cnki.net/kcms/detail/32.1180.TP.20240923.0927.002.html>
- [16] Y. Xue and B. Cai, “An optimal algorithm for iterating over planning target and evolutionary path,” CN108446792, Nov. 5, 2021.
- [17] Y. Xue. (2021, Oct.). System science in optimization of carbon neutrality pathway. [Online]. Available: <https://mp.weixin.qq.com/s/q2BcRUQ-7dQ0D2VXFGYwSrA>
- [18] Y. Xue, D. Xie, Y. Lai *et al.* “A method and system for optimizing energy transition taking into account power congestion,” CN111008769B, Sept. 6, 2022.
- Mingyu Yang** received the B.E. degree from Shandong University, Jinan, China, in 2020. She is currently pursuing the Ph.D. degree in electrical engineering at Shandong University. Her research interests include modeling and simulation of low-carbon energy transition and cyber-physical-social system in energy (CPSSE).
- Yusheng Xue** received the B.E. degree from Shandong University, Jinan, China, in 1963, the M.S. degree from the State Grid Electric Power Research Institute, Nanjing, China, in 1981, and the Ph.D. degree in electrical engineering from the University of Liège, Liège, Belgium, in 1987. His research interests include power system stability control, security, and economic operation, energy transition, and CPSSE.
- Bin Cai** received the B.S. degree in automation and the Ph.D. degree in control science and engineering from Nanjing University of Science and Technology, Nanjing, China, in 2007 and 2014, respectively. His research interests include low-carbon energy transition simulation and optimization, energy policy, and CPSSE.
- Feng Xue** received the B.E. degree from Shanghai Jiao Tong University, Shanghai, China, in 1992, the M.S. degree from the State Grid Electric Power Research Institute, Nanjing, China, in 1998, and the Ph.D. degree from the University of Bath, Bath, UK, in 2008. His research interests include power system security and reliability, energy transition, and CPSSE.