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Dynamic Modeling of Policy-Driven Power Sector Transition: Insights from the Energy–Water–Carbon Nexus

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To address the climate crisis, policy interventions are driving a structural transition in the power sector, which potentially alters the evolutionary trajectories of related carbon emissions and water consumption. Based on China's 2060 Carbon Neutrality Initiative, an integrated system dynamics model was developed to analyze the power generation transition and its interlinked impacts on decarbonization and water sustainability, considering policy-driven electricity generation and the energy–water–carbon nexus. The model was applied to China over the period 2000 to 2060. Results indicate that by 2060, China's electricity demand is projected to surge to 13 trillion kWh, with thermal power generation peaking around 2030 before declining to a lower level. This process would achieve cumulative reductions of 65 gigatons of carbon emissions and water savings of 60 km^3. Wind and solar power are expected to account for 70% of the total amount, becoming the primary substitutes for the phased-out thermal power capacity. Scenario simulations reveal that this can enhance synergistic benefits for carbon mitigation and water conservation. However, the deployment of carbon capture and storage technologies may introduce a trade-off between carbon reduction and water consumption. To mitigate this issue, integrating water-saving devices as air-cooled units into power production chains could offset additional water consumption. Clearly, the phaseout of thermal power represents a pivotal measure for optimizing the power industry. The substitution by high-quality energy products will benefit carbon emission reduction and sustainable water utilization, yet when deploying new technologies, the integration of functional and efficient technologies should be taken to prevent unintended trade-offs.

Introduction

Mitigating the effects of climate change, global warming, and environmental degradation has become an international challenge [1]. Keeping carbon emissions at a minimum is upgraded to an economic and international political issue. In this context, the Paris Agreement proposes an expectation to urge net-zero emissions around 2050, that is, carbon neutrality [2]. Over 130 countries have made efforts to realize this vision, covering approximately 90% of the gross domestic product (GDP), 85% of the population, and 88% of carbon emissions globally [3]. Among them, China, the world's largest developing country, released its first national climate policy in 2007 and declared a target of "adopting more effective policies and measures to peak carbon dioxide emissions before 2030 and strive to achieve carbon neutrality before 2060" at the 2020 United Nations General Assembly [4]. Given its fossil-dominated energy structure and ongoing industrialization/urbanization, there exists an imperative for the accelerated optimization of energy systems [5]. Via reshaping production–consumption paradigms and even inducing important shifts diverging from negative trajectories, policy interventions represent a pivotal mechanism for driving changes in the energy structure [6]. As the dominant energy contributor, the power sector constitutes a critical object for systemic regulation [7].

The power sector transition demands giving attention not only to carbon reduction benefits but also to whether the high-water-consuming nature of traditional production technologies exacerbates water pressures [8]. This manifests as complex interactions that may trigger cascading consequences. For instance, fossil-fuel-dominated power generation continuously elevates carbon emissions and requires substantial cooling water, posing reciprocal threats to water security [9]. Meanwhile, clean energy projects that neglect water-carrying capacity could lead to ecological damage and investment waste, creating a triple dilemma of "emission reduction, supply security, and ecological protection". From a sustainability perspective, although such a transition can advance Sustainable Development Goal 7 (SDG7; Clean Energy) and SDG13 (Climate Action), the widespread adoption of new energy technologies may intensify water stress (SDG6); the resulting unexpected trade-offs may further restrict responsible production (SDG12), economic growth (SDG8), and sustainable communities (SDG11). Therefore, policy design should integrate the water–energy–carbon nexus to achieve synergistic advancement of multiple SDGs rather than a zero-sum game.

In China, the world's largest developing economy and carbon emitter, it has become the primary carbon dioxide (CO_2) emission source and the second largest water-consuming sector [10,11]. In response to the resulting environmental issues and resource scarcity, China mandated an overhaul of electricity generation [12]. Investigating the evolutionary trajectories of China's power sector, with a focus on policy-driven dynamics and energy–water–carbon interactions, can provide valuable references for sustainable energy governance. In this study, an integrated system dynamics (SD) model considering China's 2060 Carbon Neutrality Initiative, the power sector transition, and the energy–water–carbon nexus is constructed to unravel the cascading effects of energy policies on carbon mitigation and water sustainability. The literature and evaluation section are shown in the following part. Methods includes the model and methodology part. Results presents the simulation results. Discussion discusses the energy–water–carbon nexus and policy implications. Finally, the empirical findings and conclusions are provided in the last part.

Literature review

The end-use electrification trend is concentrating energy transition efforts on the power sector, which is inherently driven by the proposed policy initiatives [13]. During this process, previous studies have extensively examined the macrocharacteristics of energy consumption and structural substitution among different energy types within power systems [14,15], as well as the development of renewable energy and phaseout of obsolete production capacities [16,17]. Beyond specializing on the energy sector directly, investigations further assess the power sector's sustainability through resource–environmental impact analyses, particularly emphasizing 2 critical dimensions: (a) carbon emission quantification, which is closely associated with global warming [18], and (b) water footprint evaluation, considering its widespread scarcity constraints [19].

The reduction efficacy of carbon emission related to technology-specific equipment retrofitting and targeted deployment of advanced units in energy transition is firstly a focal point of attention. In the studies of Yang et al. [20,21], the environmental effects of carbon capture, utilization, and storage technology deployment in energy industries and the CO_2 footprints of infrastructure construction in wind turbine replacement were interpreted, respectively. Other literature focuses on spatial–temporal variations and coordinated allocation of water use and virtual flows in energy transitions. For instance, based on the input–output method, Wang et al. [22] revealed a shift in virtual transfers of water withdrawal for China's energy sectors from water-deficient to water-abundant coastal areas, and Liu et al. [23] investigated water flows embodied in energy trade in Kazakhstan and identified key energy activities consuming water. Furthermore, process-based water demands for producing and supplying different energy products have also been measured via life cycle analysis [24].

Obviously, carbon emissions and water consumption in the power sector are generally treated separately, although they are proven to be not independent. With the escalating pressures from resource shortages and climate changes, more efforts exist to visualize the dynamic interrelationships among energy–water–carbon during the power sector transition [25]. Two technique tools are commonly employed to quantify the interactive impacts between power utilization, carbon mitigation, and water consumption. As Zhang et al. [26] did, an integrated framework was developed through combining The Integrated MARKAL-EFOM System (TIMES) with a water module to project CO_2 and water constraints on a power generation portfolio. Similarly, based on the Long Range Energy Alternatives Planning System (LEAP) and Integrated Policy Assessment (IPAC) model group, changes in water use and energy demand were forecasted under the carbon-neutral transformation path [27,28]. However, they are generally prefabricated models, which are designed for specific scenarios and mainly exhibit optimal performance for the particular conditions for which they were designed. In other cases, some complex optimization models have been employed to examine the trade-offs between water consumption and carbon emissions in the electricity mix. Among them, Zhang et al. [29] revealed the asymmetric interactions between low-carbon development and water constraints in China's power sector; Mamaghani et al. [30] found that the power and water sectors will get more interdependent, during which renewable energy can reduce potential carbon emission; Tang et al. [31] identified the optimal power technology layout under water–carbon cocurrent constraints. It can be found that this kind of technique is typically composed of extensive codebases and requires scholars to have a solid mathematical and programming foundation, which often results in less ease of use for practical application. Overall, the abovementioned models mostly exhibit limited adaptability to divergent conditions and do not easily allow additions to the modules provided. This calls for more efforts on developing flexible models that support modular reconfiguration and user-friendly customization to ensure broader applicability when modeling energy–water–carbon interactions in power sector transition, especially considering the driving forces of policies [32].

SD modeling functions as a powerful and flexible ex ante evaluation approach with a well-established software platform. It excels in visualizing dynamic interactions in question through iconographic interfaces and enables scenario design without coding requirements [31]. These features can greatly enhance modeling generality, thereby attracting great interests of researchers in energy development planning. Related SD models have generally been well positioned to project the electricity demand volumes of different industries at urban or regional scales and to analyze trends in energy consumption patterns under localized pilot scenarios (e.g., industrial restructuring and infrastructure projects), for instance, in the works of Jia et al. [33], Arias-Gaviria et al. [34], and Hosseini et al. [35]. However, these models exhibit limitations in comprehensively evaluating the optimization effects of macrolevel policy interventions on power systems, particularly regarding systemic assessments of energy–water–carbon nexus impacts under such strategic implementations. For this, a few studies have been done; for example, Lv et al. [36] made efforts on developing an SD model for the water–energy–food–carbon nexus to evaluate its integrated security, and Diao et al. [37] used energy factors as internal variables and constructed a water–carbon–economic model coupling SD and Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) to quantify dynamic socioeconomic processes and spatial ecological patterns. To some extent, although these attempts can help simulate the supply and demand of regional resources as well as carbon emissions, they still did not fully consider the potential impact of policy-driven changes on the power sector and the linked water–carbon elements.

Contributions and originality

Overall, the research gaps include the following: (a) Existing studies often analyze carbon emissions and water consumption in the power sector independently, despite their proven interdependencies. (b) Most current analytical tools in this field lack adaptability to divergent conditions and are not easily expandable for integrating new modules. (c) Previous SD models have not adequately incorporated the effects of policy-driven shifts on the power sector and its interconnected water–carbon systems. To bridge these research gaps, this study developed an integrated SD model tailored for analyzing power sector transition under policy-driven scenarios, with consideration of the energy–water–carbon nexus. Firstly, anchored in China's Carbon Neutrality Initiative as the policy implementation paradigm, the model integrates structural shifts in power generation portfolios into a systemic analysis. Secondly, by coupling evolution pathways in the power sector with resource use dynamics, the model enables simulation of carbon emission trajectories and water consumptions across alternative transition scenarios. Thirdly, instead of traditional tools with fixed module design and complex processing procedures, it can flexibly evaluate the synergistic impacts of national energy strategies on carbon reduction and water conservation, which is conducive to offering policymakers evidence-based insights into trade-offs and co-benefits among climate mitigation, energy availability, and resource security objectives.

Methods

Model description

Figure 1 illustrates the conceptual framework that elaborates the driving–response relationships of energy–water–carbon in power sector transition. Electricity demand is highly related to the socioeconomic needs of different industries while also deciding the power sector activities of diverse electricity products. Oriented by transition policies indicated by China's 2060

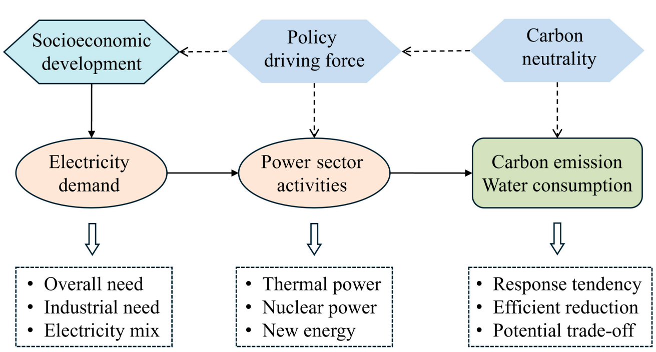

Fig. 1. Conceptual framework of energy–water–carbon relationships in the power sector.

carbon neutrality, the development pathways and internal structure of power generation will change and can affect the corresponding carbon emissions and water consumption.

The main variable groups and their causal relationships designed in the model are illustrated in Fig. 2. The core assumption posits that the total electricity demand (determined by factors such as incremental drivers, structural coefficients, and unit consumption) can be met through the electricity production of various electricity generation types (mainly related to structural factors and policy factors); that is, there is a balance between supply and demand. The trend changes in electricity generation and the resulting water consumption and carbon emissions are extrapolated based on electricity generation types and related consumption intensities and emission coefficients under hypothetical pathways.

Model disaggregation and formalization

Among SD models, STELLA, the well-established software package, is widely employed for analyzing and visualizing complex causal–effect mechanisms. Its icon-based modeling environment facilitates the construction of causal–effect diagrams and stock–flow relationships, which enables researchers to mathematically characterize dynamic interactions between subsystems with remarkable flexibility. Thus, an SD model named China's Power Sector Transition Model (CPSTM) was developed using STELLA. The time period of concern was from 2000 to 2060, which is consistent with the carbon neutrality policy. CPSTM consists of 3 modules, i.e., the socioeconomic module, power generation module, and nexus impacts module. The details of the model are provided in the Supplementary Materials, with the main disaggregation shown in the "Socioeconomic module" to "Policy-driven pathways and scenarios" sections.

Socioeconomic module

The required electricity consumption in total is driven by 2 primary factors, namely, economic development and household needs. It assembles the electricity demand of 3 major industries, which is simulated by GDP, structural coefficients, and respective consumption intensity, as empirical studies have conducted [38,39]. The electricity consumed by household living is tied to population size and demand per capita, and it generally appears to be controlled by the net population growth rate, as shown by Xue et al. [40].

Power generation module

In this module, electricity generation ways based on thermal power, nuclear power, and renewable power are introduced (Eq. (1)). Among them, thermal power generation consists of coal-fired and gas-fired options (Eqs. (2) to (4)), while electricity production based on renewable energy involves solar power, wind power, and hydropower (Eq. (5)). Considering the limitation of fossil energy reserves, the development rule of thermal power should conform to the Hubbert theory [41], while hydropower is expressed by an S logistic curve. The other types of power generation can be estimated by extrapolating the overall trend of their changes.

$$TEC = ET + EN + ENu \tag{1}$$

$$ET = K_0\left(T_t - H_y\right)^2 + H \tag{2}$$

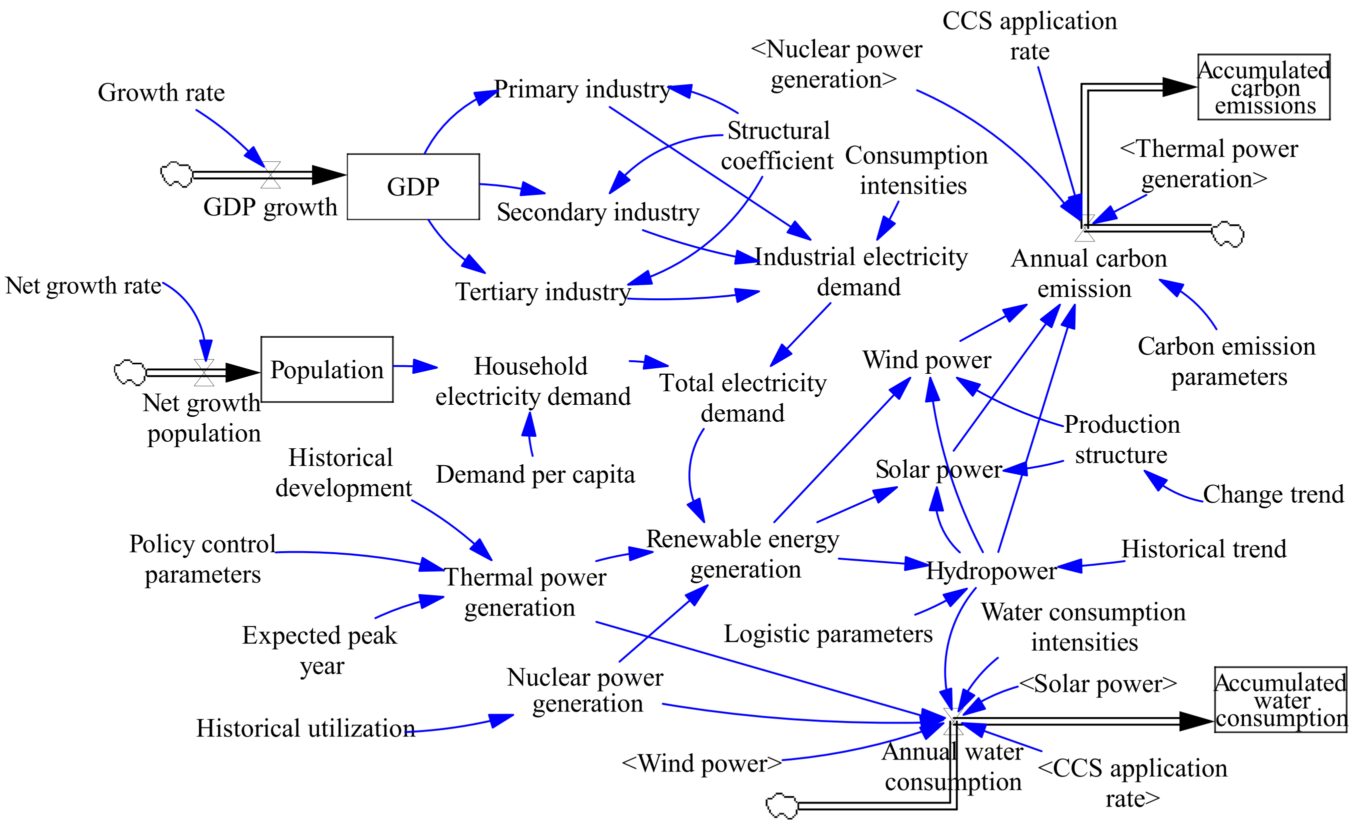

Fig. 2. Schematic diagram of the causal relationship of model variables. GDP, gross domestic product; CCS, carbon capture and storage.

$$EG = f_g \times ET \tag{3}$$

$$EC = f_c \times ET \tag{4}$$

$$EN = \sum EN_i \tag{5}$$

where *TEC* indicates the total electricity consumption in China; *ET*, *EN*, and *ENu* represent electricity generation based on thermal power, renewable energy. and nuclear power, respectively; T_t means the simulation year; H_y, H, and K_0 mean the fit parameters; f_g and f_c are the structural coefficients; and En_i is the different renewable energy types mainly including wind power, solar power, and hydropower.

Nexus impacts module

The resource–environment nexus impacts are quantified to provide information on future carbon emissions and water consumption due to power sector development in this study. They can be estimated by the volumes of different power production activities and the corresponding intensities of carbon emissions and water consumption, as shown in Eqs. (6) and (7). Given the varieties of cooling equipment in coal-fired power generation, the submodel further matches the intensity coefficients for circulating cooling units, direct-current-cooling units, air-cooling units, and seawater-cooling units. In addition, the coefficient differences caused by the combination of cooling methods and carbon capture and storage (CCS) technology are also integrated in the model.

$$CE = \sum \left(EQ_i \times IN_{ic}\right) \tag{6}$$

$$WC = \sum \left(EQ_i \times IN_{iw}\right) \tag{7}$$

where *CE* and *WC* indicate the total carbon emissions and water consumption, respectively; EQ_i represents the quantity of different electricity generation methods; and IN_{ic} and IN_{iw} mean the intensities of carbon emissions and water consumption, respectively.

Policy-driven pathways and scenarios

China's 2060 carbon neutrality policy may bring a turning point in the development trend of thermal power; thus, the pathways of business as usual (BAU) and the transition of thermal power are compared initially when modeling in this model (Table 1). Driven by this policy, the internal structures and scales of the power sector will change to different extents, which need to be further clarified. For this, 4 scenario sets are designed from the following perspectives, i.e., transforming from coal-fired to gas-fired power, replacing thermoelectric power by renewable energy power, applying CCS technology in power units, and promoting air-cooled units in electricity generation. Detailed descriptions are provided in Table 2.

Data sources

Based on the reports from the World Bank and the 14th and 15th Five-Year Plans of China, the growth rate of GDP and population was adopted for socioeconomic prediction for China. The data of power sector and related intensities of carbon emissions and water consumption were primarily collected from statistical yearbooks and annual government sectoral reports as well as reference papers. More data sources in detail are listed in the Supplementary Materials.

Table 1. Policy-driven power section transition

Pathway	Implication
Business as usual	The development scale of thermal power is extrapolated based on historical data.
Policy-driven transition	Driven by the 2060 carbon neutrality policy, the scale of thermal power will peak around 2030 and gradually exit after that, with others maintaining the current development situation.

Table 2. Electricity generation scenarios toward thermal power phaseout

Scenario	Implication
Coal-to-natural gas (CTN)	The rest of coal-fired electricity will be phased out, while the contribution of gas-fired electricity on thermal power will reach 0% (CTN0.00), 25% (CTN0.25), 50% (CTN0.50), 75% (CTN0.75), and 100% (CTN1.00) by 2060.
Thermal-to-renewable energy (TTR)	Renewable energy will be solar and wind power to further meet 0% (TTR0.00), 25% (TTR0.25), 50% (TTR0.50), 75% (TTR0.75), and 100% (TTR1.00) of the thermal electricity generation.
CCS technology application (CCS)	The application proportion of CCS technology will reach 0% (CCS0.00), 25% (CCS0.25), 50% (CCS0.50), 75% (CCS0.75), and 100% (CCS1.00) in coal-fired power units.
Air-cooled unit promotion (ACU)	Air-cooled equipment for coal-fired power units will be applied, of which the proportion will further increase to 0% (ACU0.00), 25% (ACU0.25), 50% (ACU0.50), 75% (ACU0.75), and 100% (ACU1.00) by 2060.

Results

Model validation and analysis

With paramount consideration for data integrity, CPSTM was run for China's power sector transition from 2000 to 2022 with a unified statistical caliber, while the total electricity consumption and thermal power generation data were reserved for model validation. As shown in Fig. 3, the modeling results matched well the historical records from the statistical yearbook, which illustrated the robustness and acceptable performance of this model. Moreover, it is clear to see that the consumption of electricity in China showed a nearly linear and rapid growth trend during the early 21st century, more than quadrupling from less than 2 trillion kWh (10^{12} kWh = 1 TWh) to over 8 TWh around 2020. During the same period, such growth drove the development of the power sector, with thermal power occupying a dominant position, which accounted for over 90% in the first 5 years. After that, the growth rate of power production scale substantially decreased from 2010 to 2020, causing the proportion gradually to reduce to about 75% in the later period. This change is closely related to the requirement for air quality and also reflects the tendency and potential of the proactive transformation of the power sector.

Socioeconomic development and total electricity demand

According to simulation results, China's GDP is projected to progressively increase from 102 trillion to 396 trillion yuan, while the permanent resident population is expected to decrease by approximately 340 million from the current 1.4 billion (Fig. 4A). The growth trajectory of total electricity demand and substitution among internal components should exhibit intricate interplay with socioeconomic development patterns. As illustrated in Fig. 4B, China's future electricity demand maintains an upward trend, rising from 8 TWh in 2020 to 13 TWh by 2060, with an average increment of 2 TWh per 2-decade interval. Structurally, the secondary industry will remain the dominant driver of incremental electricity demand throughout the simulation period. Although its proportional contribution to total demand is estimated to decline from ~70% in 2020 to <60% by the terminal phase, it will retain paramount importance. Concurrently, the tertiary sector's contribution to electricity demand growth will demonstrate marked expansion, increasing from 10% in 2020 to a projected 30% by 2060, thereby emerging as the second largest contributing sector. In contrast, the primary sector consistently occupies a marginal share, while electricity consumption for supporting

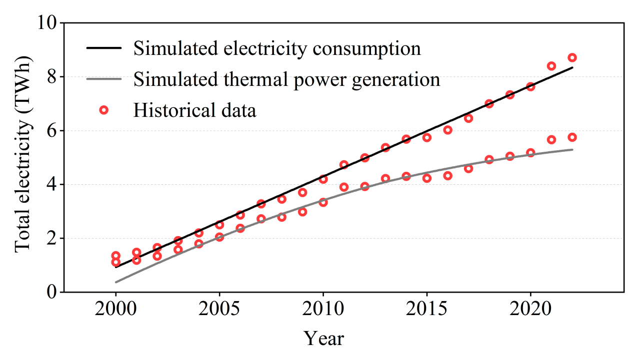

Fig. 3. China's Power Sector Transition Model (CPSTM) model validation and historical trends of the power sector.

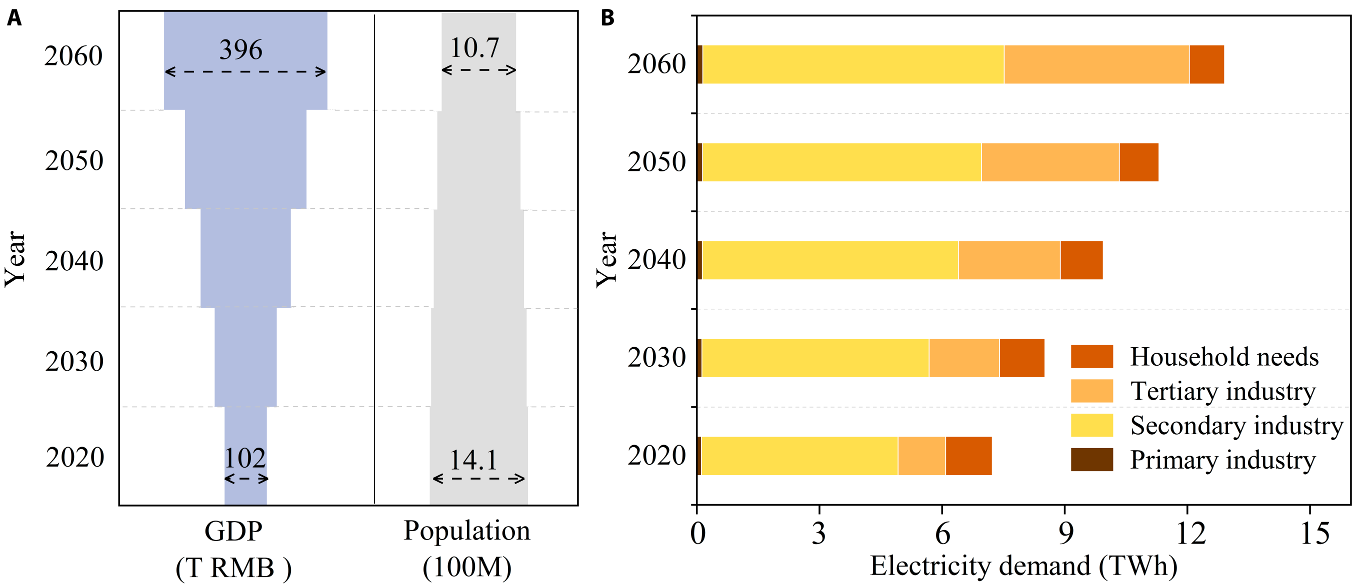

Fig. 4. Future socioeconomic development (A) and electricity demand (B) in China. Note: T RMB represents trillion (10^{12}) yuan, and 100M indicates 100 million population.

household needs will maintain a relatively important proportion (~10% on average) with marginal downward adjustment over the study horizon.

Policy-driven thermal power transitions and potential impacts

Projecting solely based on historical evolutionary patterns, China's thermal power generation capacity would logically continue its upward trajectory. As simulated (Fig. 5), under the BAU pathway, thermal power output would escalate to nearly 7 TWh by 2060—marking a 2-TWh increase relative to current production levels. However, under the impetus of China's 2060 Carbon Neutrality Policy, the power sector is projected to undergo transformative structural shifts. Specifically, thermal power generation will deviate from its historical growth trajectory, peaking around 5.7 TWh by 2030 before entering a phase of gradual decline. This policy-driven pathway would result in the output plummeting below 2 TWh by 2060, representing a 5.5-TWh reduction compared to that of the BAU pathway. Such divergence underscores the profound impact of decarbonization policies on reshaping China's energy production paradigm.

During this period, the cumulative reductions in carbon emissions and water consumption resulting from these measures will progressively increase. It is estimated that in the 2020s to the 2030s, the cumulative CO_2 reduction will reach approximately 8.63 gigatons (Gt) (10^9 tons = 1 Gt) of CO_2, accounting for about 14% of the total reduction over the entire simulation period. This figure is slightly less than the total reduction in the 2040s, which amounts to 16.47 Gt of CO_2. Notably, the final decade (2050s) will witness the most substantial carbon emission reductions from thermal power production, peaking at nearly 33 Gt. Coupled with the additional 4.29 Gt CO_2 reduction in 2060 alone, the cumulative carbon emission abatement over the 4-decade period will reach 61.57 Gt—a volume equivalent to approximately 35 years of the global carbon sequestration capacity of the Amazon rainforest. A comparable reduction pattern will be observed for the water consumption of thermal power generation, with cumulative abatement over the simulation period totaling approximately 57 km^3 (10^9 m^3 = 1 km^3). This volume equates to 15 years of the total water demand for Beijing, a megacity with a population exceeding 23 million. Among them, the reduction amounts in 2020s and 2030s will total 3.07 and 7.13 km^3, respectively. The latter 2 decades (2040s to 2050s) will account for nearly 83% of the total water consumption reduction during the simulation period, with the 2050s alone contributing approximately 60% of this reduction.

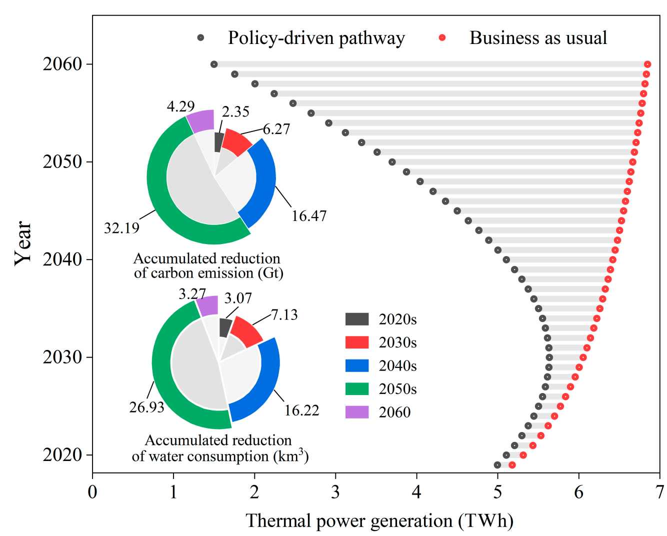

Fig. 5. Thermal power phaseout and reductions of environmental impacts.

Electricity mix substitution triggered by thermal power phaseout

To meet the national electricity demand, the reduction in thermal power capacity should be compensated for by other energy sources, resulting in an obvious transformation in China's electricity mix. As illustrated in Fig. 6, coal-fired power will always dominate thermal generation, while gas-fired power—although projected to increase marginally—will remain a minor contributor.

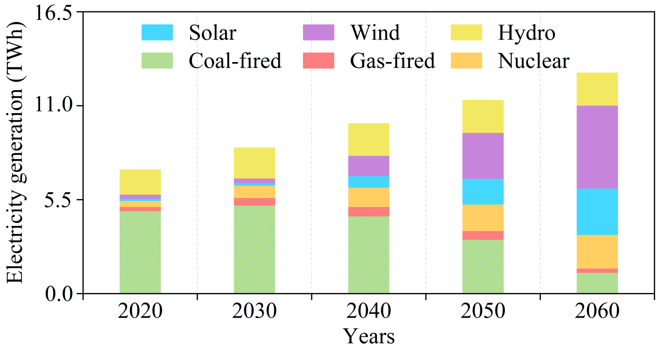

Fig. 6. Electricity mix by production type from 2020 to 2060.

Under policy-driven thermal power phaseout initiatives, renewable energy adoption will exhibit optimistic growth prospects, with its share in total power generation expanding from less than 25% in 2020 to over 73% by 2060. Among renewables, hydroelectric power will experience moderate growth before stabilizing at mature levels. Solar power generation will flip multiple times by 2060, evolving from negligible levels to becoming the second largest power source. Notably, wind power will demonstrate the most rapid expansion, reaching about 40% of total generation by 2060. This trajectory is obviously driven by emerging national strategies accelerating wind/solar infrastructure development, including rural wind and solar access and integrated wind–solar–storage system construction. Concurrently, nuclear power will also emerge as an essential part in the energy transition, with an approximately 15% generation share by 2060.

Water–carbon nexus under electricity generation scenarios

On the basis of implementing power transition policies, there are multiple potential options that will further trigger fluctuations in resource and environmental impacts, leading to synergies or trade-offs among multiple subsystems. As shown in Fig. 7, the future trends of carbon emissions and water consumption in China's power industry under different scenarios are undergoing changes.

At the structural optimization level, carbon emissions are more sensitive to the substitution scale of renewable energy (Fig. 7C). Specifically, within the TTR scenario group, if no substitution occurs (TTR0.00), despite the positive effects of the thermal power phaseout, carbon emissions will exhibit a peak trend (reaching a maximum of approximately 4.84 Gt of CO_2 around 2030); there remains marked potential for CO_2 reduction. As the substitution rate increases (from TTR0.25 to TTR1.00), the peak-shaving effect becomes evident, with carbon emissions gradually decreasing to notably lower levels by 2060. This implies that vigorously promoting and accelerating the popularization of renewable energy is conducive to achieving carbon emission reduction goals more effectively. Meanwhile, this also leads to a similar optimization effect in reducing water consumption, with water usage decreasing from a peak of 12.25 km^3 under TTR0.00 to less than 11 km^3 under TTR1.00 and the peak time advancing by approximately 5 years. Comparatively, under the TTR scenarios, the potential for carbon emission reduction under the CTN scenarios is relatively limited, with the maximum carbon emissions during the simulation period falling within the range of approximately 4.5 ± 0.4 Gt, as shown in Fig. 7A. Similarly, the sensitivity of water consumption to the contribution of gas-fired electricity to thermal power is also not that high (Fig. 7B), with the lower limit of the peak water usage being around 11.5 km^3 and decreasing to approximately 7.25 km^3 by 2060.

At the technology application level, the deployment of CCS equipment will indeed exert a positive effect on reducing carbon emissions (Fig. 7E). With its widespread adoption, its driving role becomes prominent in the latter half of the simulation period (between 2040 and 2050), particularly evident under the CCS1.00 scenario, where carbon emissions are projected to drop below 1.5 Gt after 2046. However, it should be noted that as the application rate of CCS increases, the corresponding peak water consumption may substantially rise and be delayed, reaching a maximum of 14 km^3 around 2045, which is 15% higher than that in the baseline scenario (CCS0.00), as shown in Fig. 7F. Clearly, there will exist a trade-off effect, necessitating rational planning or the implementation of additional preventive measures in practice. Then, in Fig. 7G and H, the application of air-cooling devices will primarily demonstrate favorable results in reducing water consumption. The widespread promotion of air-cooling technology, namely, the condition under the ACU1.00 scenario, will lead to an additional average reduction in water consumption of approximately 1.2 km^3 compared to the baseline pathway. The scenarios of ACU0.25, ACU0.50, and ACU0.75 all fall within this range.

Discussion

Energy–water–carbon synergies and trade-offs in the power sector

Energy mix transition in the power system is conducive to bringing synergy. Scenario analysis results indicate that whether it is replacing coal power with gas power generation or complementing retired thermal capacity with renewable energy deployment, it can consistently yield certain positive effects across 3 dimensions: greening of the energy system, reduction of carbon emissions, and strengthening of water-saving effects. This primarily stems from the inherent shortcomings of conventional coal-dominated, resource-intensive thermal power sectors—characterized by large-scale operations, relatively low unit efficiency, and elevated emissions—contrasted against the energy attributes of gas-fired generation and renewables, including low-carbon profiles, high conversion efficiency, and systemic optimization potential [42]. That makes the utilization of these positive energy products play an indispensable role in the current trend of energy transition. In fact, from the perspective of historical trends and future development, this substitution process seems inevitable. This is also in line with the international sustainability agendas as SDGs, which advocates doubling the global rate of improvement in energy efficiency while scaling up renewable energy's share in the energy mix [43]. However, the rhythm requires strategic foresight and systematic planning; that is, the introduction of large-scale novel renewables necessitates rigorous life cycle assessment. For instance, biofuel production within the larger boundaries of life cycle assessment further expanding to involve factory construction, equipment manufacture, and device maintenance may paradoxically increase additional carbon emissions, thereby weakening efforts to enhance environmental benefits.

The prudent adoption of emerging technologies in energy transition requires careful consideration. Research indicates that

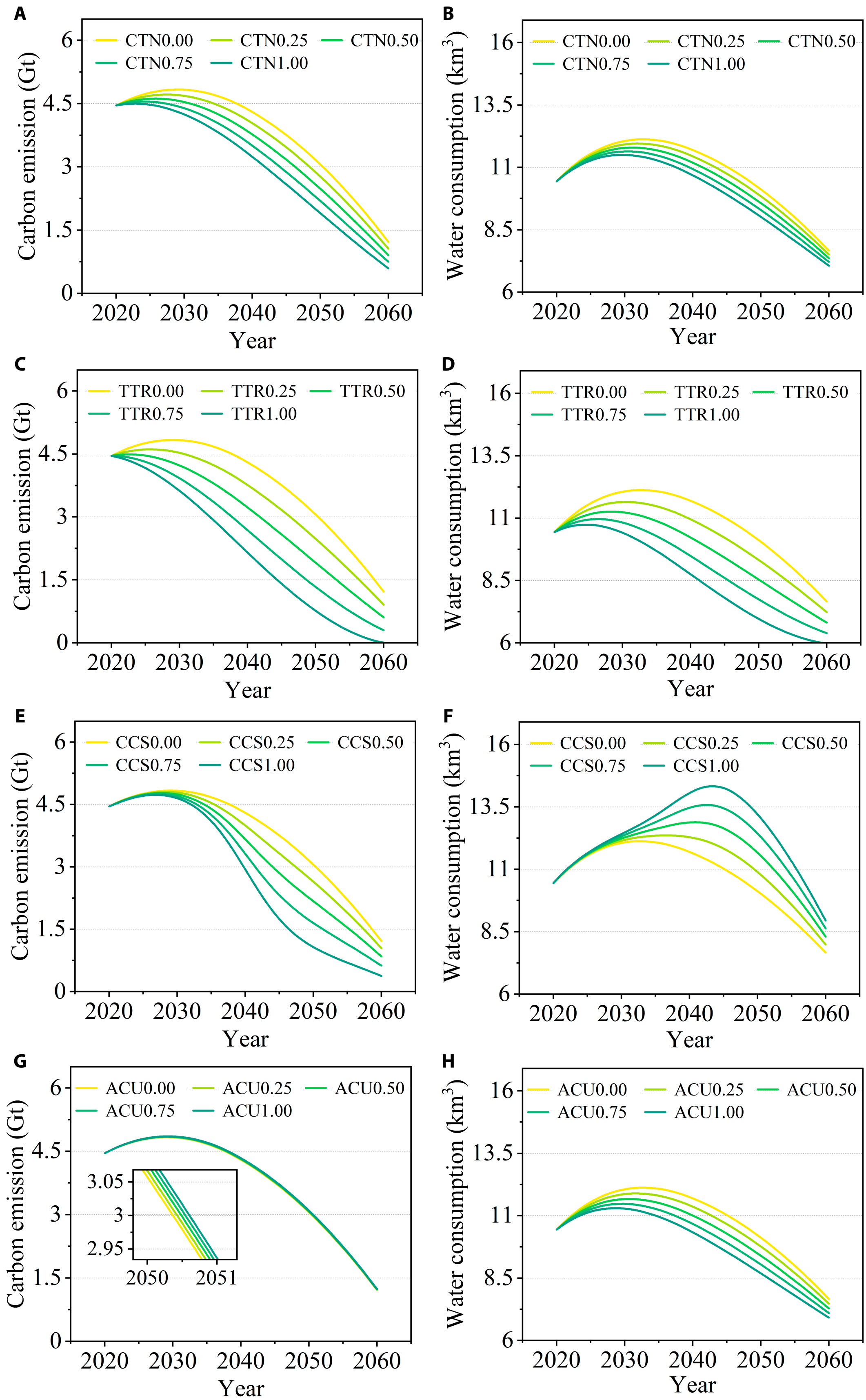

Fig. 7. Carbon emissions and water consumption under electricity generation scenarios. Note: (A), (C), (E), and (G) show the carbon emissions respectively under the scenarios of CTN, TTR, CCS, and ACU, while (B), (D), (F), and (H) show the water consumption correspondingly.

the integration of CCS may induce carbon–water trade-offs to some extent. Similarly, Xie et al. [8] also demonstrated that the water savings and carbon emission reduction achieved through energy transition are insufficient to offset the additional resource consumption and environmental impacts incurred by rapid CCS utilization. Thus, implementing CCS demands a thorough understanding and the formulation of concise strategies to mitigate these trade-offs. It is possible to consider replacing hydraulic fracturing water with captured CO_2 to reduce additional water consumption [44]. In contrast, the utilization of air-cooled units exhibits unidirectional water-saving enhancement but exerts limited constraints on carbon emissions. In practice, power generation processes often involve hybrid deployment of multiple technologies, where positive mitigation benefits (e.g., carbon reduction and water conservation) and negative driving forces (e.g., increased energy/water demands) may superimpose, creating complex trade-off relationships. For instance, integrating air-cooled units at the front end of the power supply chain and deploying CCS at the back end could potentially achieve the dual benefits of carbon mitigation and water consumption reduction. This still requires empirical validation through pilot testing to optimize integration modalities and proportions.

Policy suggestion for power sector transition

The decarbonization of power systems typically progresses through 2 phases: quantitative transformation and structural transformation. The total volume changes refer to the process of decoupling economic development from high-carbon energy consumption, which involves eliminating dependence on highly polluting energy products and improving environmental quality while promoting social development. As Aydin and Erdem [45] emphasized, this phase demands profound economic planning. This necessitates a clear development paradigm that balances economic growth scale and pace within environmental and resource constraints. For instance, Li et al. [39] demonstrated that the high-density development pathway often led to energy demand exceeding local availability, perpetuating a high-risk shortage tension; conversely, adjusting the economic growth rate appropriately to an acceptable level can enhance energy security and has potential to greatly reduce carbon emission and water consumed by energy industries—thereby aligning with the SDGs.

Regarding structural transformation, we argue that continued retrofitting of traditional coal-dominated power plants remains essential, with gradual substitution by green and clean energy sources. Given coal's high-carbon nature, the phaseout of coal-fired power in the early stage means a lot for China's carbon neutrality objectives. Zhang et al. [46] discussed the decoupling process between coal consumption and GDP growth during decarbonization, attributing it to the modification/elimination of coal-intensive industrial processes. Their work also validated the positive role of coal-to-electricity and coal-to-gas conversions in optimizing thermal power sectors for carbon reduction and environmental impacts. This can drive the utilization of renewable energy to make up for the temporary decline in production capacity and form the main dominant energy in the future. Projections in our study indicate that wind and nuclear energy could supply up to 75% of the total, underscoring their substantial decarbonization potential.

To achieve this, it still requires the cooperation of paradigm shifts in policies, institutions, technology, and so on. On the policy front, implementable strategies should improve green energy productivity and adoption through ecological design frameworks, subsidies for renewable development/maintenance, and preferential investments in environmental technologies. The European Union's countries have implemented the highest annual energy investment, with an effect accounting for about 20% of energy savings [10]. Cutcu et al. [47] also argued that governments should allocate affordable and easily accessible funding for initiatives mitigating negative impacts on natural resource sustainability. Institutional reforms are equally critical, including project approval criteria, incentive/penalty mechanisms, tax incentives, and even energy laws. Aydin et al. [48] proposed that designing fuel rules would provide contemporary and sustainable energy management for countries such as Austria and the Netherlands. Carbon trading markets also offer transitional compensation for coal-dependent electricity industries [8]. In addition to this, the bottleneck often lies in technology. The rapid growth of green energy may put the power system in a fragile state; for instance, photovoltaic and wind power rely on local weather conditions and have strong spatiotemporal fluctuations. Introducing advanced machinery and equipment for hybrid-power generation, that is, coupling renewable energy with coal energy to maintain system security, is an appropriate solution [44], as is the organized combination of CCS technology, but attention must be paid to weigh water scarcity. Finally, improving the electricity infrastructure like storage and transportation networks to increase and ensure the share of stable and reliable renewable sources remains pivotal to securing a resilient, low-carbon energy future.

Limitations and prospects

Several limitations should be acknowledged in this study. Firstly, the model framework is developed from a macroenvironmental planning perspective, employing a "what-if" scenario analysis to estimate the energy–water–carbon nexus in the power sector under the carbon-neutral policy. It should be noted that some engineering details such as output costs, siting selection, and infrastructure configurations were not incorporated into the module framework, which may introduce uncertainties into the findings. Secondly, this study focused on China and did not downscale to provincial or municipal levels, limiting in providing more detailed spatiotemporal interaction simulations. Thirdly, in terms of methodological standpoint, SD models inherently rely on extrapolations of representative variables derived from empirical models sharing common structural setups and behavioral patterns. Consequently, this model, like any other dynamic simulation studies, was inevitably based on simplifications and assumptions regarding the complexity of real-world evolution.

Future research could focus on 3 areas: (a) Covering more comprehensive objectives: It requires to more clearly ground in actual policy instruments, for instance, China's Five-Year Plans, the National Emissions Trading Scheme, or renewable portfolio standards. Some environmental risks that may cause sudden damage and change the transition cycle of the power sector are also worth considering. This would enable a comparative analysis of interrelated dimensions including process-based technical optimization, ecological service function enhancement, and infrastructure resilience improvement within the broader context of China's decarbonization pathways. (b) Spatial–temporal heterogeneity analysis: The transition of the power sector and associated carbon emissions and water consumption may exhibit disparities across stages, phases, and regions along with production–supply chains. Given the spatial mismatch of resource pressures—such as water scarcity constraints in renewable energy bases (e.g., Northwest China) versus carbon reduction pressures in load centers (e.g., East China)—and temporal discrepancies in equipment depreciation schedules and cost recovery cycles, future research should prioritize developing a spatiotemporal coupling model covering the full "source–grid–load–storage" chain. (c) Enhancing the SD model: This modeling framework was well structured with high transparency and reproducibility for improvements and holds potential for extension to other metamodels or regions, facilitating comparative energy–water–carbon investigations. Possible efforts include integrating supplementary external modules within the model and establishing interoperability with techno-economic optimization models commonly used in power sector planning, such as TIMES, and platforms like ArcGIS and MATLAB, thereby enhancing model performance, precision, and practical applicability.

Conclusion

An SD model was constructed to simulate the dynamics of power sector transition and the energy–water–carbon nexus impacts driven by China's 2060 Carbon Neutrality Policy, in consideration of interactions between electricity demand and consumption as well as various electricity mixes. The results indicate that China's electricity demand is projected to surge to 13 TWh by 2060, with the tertiary sector making the primary contribution. Guided by carbon neutrality policies, the generating capacity of thermal power is expected to peak around 2030 and then decline greatly to a low level. This process will accumulate a reduction of 65 Gt of CO_2 and save 60 km^3 of water. Clearly, the phaseout of thermal power represents a pivotal measure for optimizing the power industry. In terms of energy mix, renewable energy dominated by wind and solar power will expand to account for 70% of the total energy, becoming the main alternative to thermal power. Furthermore, the substitution by high-quality energy products will promote the synergistic positive benefits of carbon reduction and water conservation, as confirmed by the simulation results of the CTN and TTR scenario groups. When deploying new technologies in the power industry, necessary measures should be taken to prevent unintended trade-offs. Specifically, although the application of CCS can substantially reduce carbon emissions, its increasing utilization rate will result in additional water consumption. This issue might be mitigated through the cross-integration of CCS with air-cooled units in power production chains considering the positive simulation results that the latter will offer favorable outcomes in water conservation without causing additional carbon emissions. The findings offer insights into policymaking, especially underscoring the positive effects of China's power sector decarbonization policy and the necessity of integrated water-energy-carbon planning of sustainable development plans.

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Competing interests: The authors declare that they have no competing interests.

Data Availability

The data used in this study are cited in the text and available upon reasonable request from the corresponding authors.

Supplementary Materials

Fig. S1
Tables S1 and S2

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Dynamic Modeling of Policy-Driven Power Sector Transition: Insights from the Energy–Water–Carbon Nexus

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To address the climate crisis, policy interventions are driving a structural transition in the power sector, which potentially alters the evolutionary trajectories of related carbon emissions and water consumption. Based on China's 2060 Carbon Neutrality Initiative, an integrated system dynamics model was developed to analyze the power generation transition and its interlinked impacts on decarbonization and water sustainability, considering policy-driven electricity generation and the energy–water–carbon nexus. The model was applied to China over the period 2000 to 2060. Results indicate that by 2060, China's electricity demand is projected to surge to 13 trillion kWh, with thermal power generation peaking around 2030 before declining to a lower level. This process would achieve cumulative reductions of 65 gigatons of carbon emissions and water savings of 60 km3. Wind and solar power are expected to account for 70% of the total amount, becoming the primary substitutes for the phased-out thermal power capacity. Scenario simulations reveal that this can enhance synergistic benefits for carbon mitigation and water conservation. However, the deployment of carbon capture and storage technologies may introduce a trade-off between carbon reduction and water consumption. To mitigate this issue, integrating water-saving devices as air-cooled units into power production chains could offset additional water consumption. Clearly, the phaseout of thermal power represents a pivotal measure for optimizing the power industry. The substitution by high-quality energy products will benefit carbon emission reduction and sustainable water utilization, yet when deploying new technologies, the integration of functional and efficient technologies should be taken to prevent unintended trade-offs.
Image

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