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Dynamic simulation of industrial synergy optimisation pathways in Beijing-Tianjin-Hebei region based on energy-water nexus

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ABSTRACT

Energy over-consumption, water shortage, and intensive carbon dioxide (CO_2) emissions are the three vital environmental issues in the context of global climate change. China is promoting the coordinated development of the Beijing-Tianjin-Hebei region as a national strategy project; this makes it more urgent to integrate water conservation, energy structure transition, and CO_2 reduction within process of high-quality development and green transformation.

This study uncovered energy-water nexus patterns within Beijing-Tianjin-Hebei, and carried out dynamic simulation research from the perspective of industrial synergy to facilitate optimization roadmaps. A Beijing-Tianjin-Hebei Energy-Water Nexus Simulator is innovatively developed, which is based on the theories of input and output, system dynamics, and dynamic multi-object planning; and is committed to revealing the regional energy and water consumption, carbon emission, and economic system developing trends. Through policy mix including industrial structure adjustment, collaborative development, and environmental efficiency improvement, multiple scenarios' comparison can provide the optimization path of Beijing-Tianjin-Hebei during 2020-2035 under overall control of muti-regional energy-water and carbon targets.

The dynamic optimization decision-making model and policy simulator developed in this study is expected to be widely used in the sustainable development planning of Chinese inter-regional economy, and provide scientific support for regional coordinated development and ecological civilization construction.

Keywords: energyenergy-water nexus; carbon reduction; industrial synergy; input-output model; dynamic simulation

NONMENCLATURE

Abbreviations	
GDP	Gross Domestic Production
CO_2	Carbon dioxide
Symbols	
t	Year
n	Industrial sector
p	Energy
τ	Social discount rate
δ	Value-added rate

1. INTRODUCTION

Water resource deficiency, energy shortage, and intensive carbon dioxide (CO_2) emissions are the three vital environmental issues in the context of global climate change. Driven by the carbon neutral pledge, China has attached substantial importance to energy transition and carbon reduction.

As a typical economic circle and urban agglomeration, the Beijing-Tianjin-Hebei region (BTH) accounts for about 8.5 percent of China's overall GDP (Beijing Provincial Bureau of Statistics, 2021; Tianjin Provincial Bureau of Statistics, 2021; Hebei Provincial Bureau of Statistics, 2021). However, environmental and resource-related problems caused by economic expansion have been particularly prominent for the past decades.

The BTH region has been facing serious water scarcity. In 2020, per capita water resources in the BTH region were about 163 m^3 (Haihe River Water Conservancy Commission, 2020) accounting for only

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approximately 7.5% of the average level in China (2189 m[3]); in Tianjin, per capita water resources accounted for only approximately 2.5% of the average level in China. Meanwhile, the BTH region has been facing severe energy shortage; the external dependence of energy of the BTH was up to 42.9% (National Bureau of Statistics of China, 2021), below the national level (18.4%); in Beijing, the level is highly 93.5%, indicating the uneven energy distribution issues. In addition, massive consumption of fossil energy in BTH inevitably aggravated intensive carbon emissions; in 2020, the CO_2 emissions per unit of GDP in BTH was 1.4 times than the national levels, and in Hebei, the level was even 2.6 times higher.

The Chinese Government has proposed the “Beijing-Tianjin-Hebei (BTH) regional coordinated development” in 2015, which aimed to create a new economic growth pole and promote a balanced evolution of the economic and resource environment to ensure the harmonious development of urban agglomeration. Therefore, it is necessary to conduct a regional-level analysis of the synergetic development of cross-regional industries under water resource, energy consumption and carbon emissions constraints.

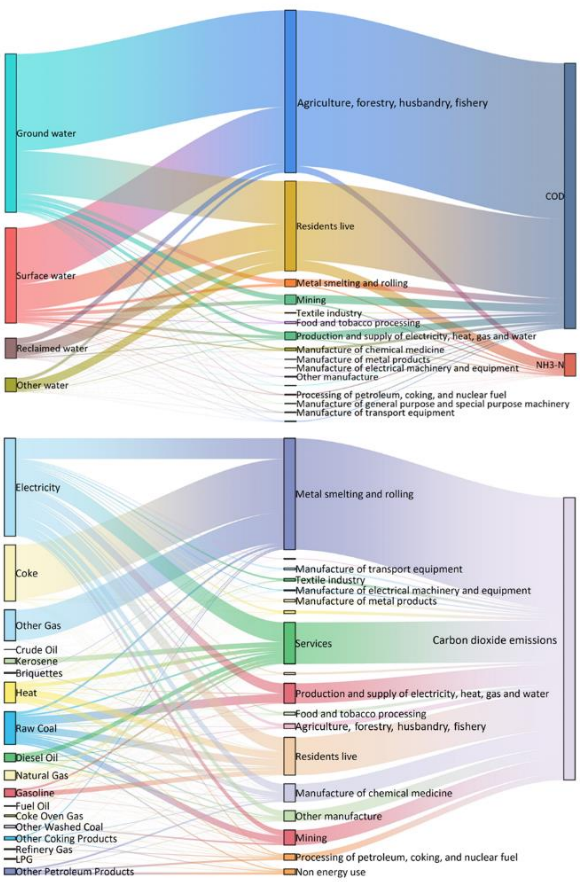

Fig. 1. The water and carbon flow of the BTH in 2020.

The existing studies about water-energy-carbon nexus among urban agglomerations exhibit great differences in perspectives, data, and methods.

From a research perspective, many scholars have focused primarily on the water-energy-carbon nexus character and efficiency (Li et al., 2020). For instance, most existing studies focused on the nexus and the material flows pattern (Tian et al., 2022), some scholars further explored the carbon or water footprint flows embodied in regional based on a multiregional input−output (MRIO) model (Wang et al., 2021; Long et al., 2022). However, studies focusing on deciphering the synergy optimisation pathways quantitatively based on water-energy-carbon nexus are relatively limited.

In most cases, research is based on national-level data (Su et al., 2023), researches based on regional level, especially on the urban agglomerations, are limited. Given the complexity of the nexus at the interregional scale, additional in-depth studies with a holistic framework from the multiple-regional and-sectoral perspective are necessary.

The methodology used in these studies are in some cases based on summarizing historical patterns or current situations focused on data statistics with predictivity limitations, while in other cases it involves further development forecasting by setting exogenous parameters, such as the regression on population, affluence, and technology (STIRPAT) model (Yu et al., 2023), the logarithmic mean Divisia index (LMDI) decomposition method (Takayabu, 2020), the long-range Energy Alternatives Planning System (LEAP) model (Huang et al., 2023), and other forecasting models (Weng et al., 2019). Nevertheless, setting the exogenous parameters ignores the interactions among energy-economy-environment (3Es) systems, which have a significant effect on the synergistic reduction of CO_2 and water pollutants (Xiang et al., 2023). This highlights the lack of system dynamics-based simulation research on the collaborative reduction of CO_2 and water pollutants that combines the input-output method with 3Es systems (Xu et al., 2021).

2. MATERIAL AND METHODS

The model framework is composed of an energy and resource system, an economic system, and an environmental system. The economic system comprises the production process and residential life, in which industrial production activities promote intermediate input and final demand, satisfy the input-output balance, and constitute the value flow.

Meanwhile, as a necessary input for economic development, water resources are provided by the water resource system and transformed into sewage after the production process. Part of the sewage is treated and converted into reclaimed water, while the rest is discharged along with water pollutants, constituting water resource flow and water pollutant flow, respectively. In addition, the energy is selected to primary energy and secondary energy, and the electricity consumption is linked with the production activities among energy system. Fossil-fuel combustion during industrial processes can emit both CO2.

Under the total amount of control of energy and water consumption, CO_2 and pollutant emissions from the three regions, the resources and emission reductions are coordinated and distributed among multiple regions, thereby promoting the synergetic development of the BTH region.

Combined with the goals of carbon peak in the BTH region on the above model formula, a dynamic simulation is accomplished using Linear Interactive and General Optimizer software.

Fig. 2 presents the framework of the research.

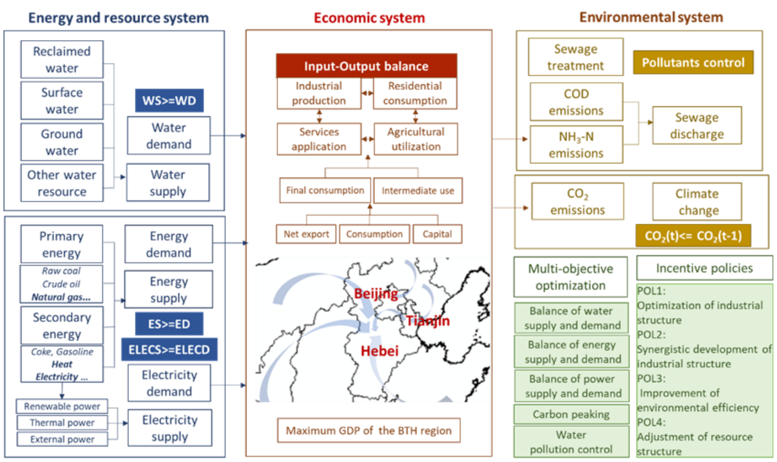

Fig. 2. The model framework of the model

2.1. Objective function

The objective of the model is to maximise economic development, defined as the maximum GDP of the BTH region, calculated using the following equations:

$$MAX \sum_r \sum_t \frac{1}{(1+\tau)^{t-1}} GDP^r(t) \quad (1)$$

$$GDP^r(t) = [\delta_1^r \quad \dots \quad \delta_{16}^r] \begin{bmatrix} x_1^r \\ \vdots \\ x_{16}^r \end{bmatrix} \quad (2)$$

where r is the region with values from 1 to 3, representing Beijing, Tianjin, and Hebei, respectively; t is the simulation period, with values from 1(2017) to 14(2035); $GDP^r(t)$ is the gross domestic production of r region in year t (en); τ is the social discount rate (5.0%, ex); $x_n^r(t)$ is the output of industry n in r region in year t (en); and δ_n^r is the value-added rate of industry n (ex). The economic system, water resource system, and water environment system are connected by industrial production. Therefore, to better demonstrate the water environment impacts brought by industries, this study categorised the industrial sector into 16 sectors n (see Table 1).

Table 1. Classification of industry sectors in 2017

n=1	Agriculture, forestry, husbandry, fishery
n=2	Mining
n=3	Food and tobacco processing
n=4	Textile industry
n=5	Manufacture of paper, printing and articles for culture, education and sport activity
n=6	Processing of petroleum, coking, and nuclear fuel
n=7	Manufacture of chemical medicine
n=8	Metal smelting and rolling
n=9	Manufacture of metal products
n=10	Manufacture of general purpose and special purpose machinery
n=11	Manufacture of transport equipment
n=12	Manufacture of electrical machinery and equipment
n=13	Manufacture of communication equipment, computers and other electronic equipment
n=14	Production and supply of electricity, heat, gas and water
n=15	Other manufacture
n=16	Services

The constraints of this model is set to peak before 2030, that is, after 2030, CO2 will decrease year by year. CO2 emission calculation can be found in 2.1.4

$$CO_2(t) \le CO_2(t-1)(t \ge 14) \quad (3)$$

2.2 Economic system

Based on input-output theory and considering industrial development and consumer demand, socio-economic models reflect the level of socio-economic development of a country or region, including intersectoral input and output, household and government consumption, net exports and population. The constraints are below:

2.2.1 Input-output balance

According to input-output theory, production and consumption in a social economy must meet an input-output balance capable of ascertaining the industrial structure of how to adjust under mutual influence.

$$\begin{bmatrix} X^1(t) \\ X^2(t) \\ X^3(t) \end{bmatrix} \ge \begin{bmatrix} A^1 & & \\ & A^2 & \\ & & A^3 \end{bmatrix} \begin{bmatrix} X^1(t) \\ X^2(t) \\ X^3(t) \end{bmatrix} + \begin{bmatrix} TC^1(t) \\ TC^2(t) \\ TC^3(t) \end{bmatrix} + \begin{bmatrix} GCF^1(t) \\ GCF^2(t) \\ GCF^3(t) \end{bmatrix} + \begin{bmatrix} NEX^1(t) \\ NEX^2(t) \\ NEX^3(t) \end{bmatrix} + \begin{bmatrix} NOF^1(t) \\ NOF^2(t) \\ NOF^3(t) \end{bmatrix} \quad (4)$$

Where $X^r(t)=\begin{bmatrix} x_1^r(t) \\ \vdots \\ x_{16}^r(t) \end{bmatrix}$ is the output value matrix of 16 industries in r region in year t (en); $A^r=\begin{bmatrix} a_{1\,1}^r & \cdots & a_{1\,16}^r \\ \vdots & \ddots & \vdots \\ a_{16\,1}^r & \cdots & a_{16\,16}^r \end{bmatrix}$ is the input coefficient matrix of r region (ex); $TC^r(t)=\begin{bmatrix} TC_1^r(t) \\ \vdots \\ TC_{16}^r(t) \end{bmatrix}$ is the total consumption matrix of r region in year t (en); $GCF^r(t)=\begin{bmatrix} GCF_1^r(t) \\ \vdots \\ GCF_{16}^r(t) \end{bmatrix}$ is the gross capital formation matrix of r region in year t (en); $NEX^r(t)$ is the net exports matrix of r region in year t (en); and $NOF^r(t)$ is the net outflow matrix of r region in year t (en);

2.2.2 Population growth model

$$PRP(t)=\sum_r PRP^r(t)$$
$$=[(1+\sigma^1) \quad (1+\sigma^2) \quad (1+\sigma^3)]\begin{bmatrix} PRP^1(t-1) \\ PRP^2(t-1) \\ PRP^3(t-1) \end{bmatrix} \quad (5)$$

where $PRP(t)$ is the resident population in the BTH region in year t (en) and σ^r is the annual population growth rate of r region, calculated based on the actual data from 2015 to 2019 (ex).

2.3 Resource and energy system

2.3.1 Water supply

The water supply comprises groundwater, surface water, reclaimed water, and other water sources. Groundwater, surface water, and other sources were assembled into freshwater.

$$WS(t)=\sum_r WS^r=\sum_r[RW^r(t)+FW^r(t)] \quad (6)$$

where $TWS(t)$ is the total water supply of the BTH region in year t (en), TWS^r is the water supply of r region in year t (en), $RW^r(t)$ is the reclaimed water amount of r region in year t (en), and $FW^r(t)$ is the fresh water supply of r region in year t (en).

2.3.2 Water demand

As a necessary resource for economic development, water demand mainly comes from industrial development and residents' lives.

$$WD(t)=\sum_r WD^r=[1 \quad \ldots \quad 1]\begin{bmatrix} \rho^1 & & \\ & \rho^2 & \\ & & \rho^3 \end{bmatrix}\begin{bmatrix} X^1 \\ X^2 \\ X^3 \end{bmatrix}$$
$$+[\theta^1 \quad \theta^2 \quad \theta^3]\begin{bmatrix} PRP^1(t) \\ PRP^2(t) \\ PRP^3(t) \end{bmatrix} \quad (7)$$
$$\rho^r=[\rho_1^r \quad \ldots \quad \rho_{16}^r] \quad (8)$$

where $WD(t)$ is the total water demand of the BTH region in year t (en); $WD^r(t)$ is the water demand of r region in year t (en); ρ_n^r is the water consumption intensity of n sector of r region (ex); and θ^r is the water consumption intensity of residents of r region (ex).

2.3.3 Water supply and demand balance

To satisfy the demand for social development, the water supply must not be less than the water demand, namely:

$$WS^r(t)\geq WD^r(t) \quad (9)$$

2.3.4 Energy supply

The direct and indirect energy flow balances were considered in this study. Energy demand was derived based on the industrial production of 16 sectors and residential living. The energy supply, comprising of 19 energy types (see Table 2), including primary and secondary energy sources, was considered in the model. Energy supply and demand were expressed by the following equations:

$$ES(t)=\sum_r ES^r(t)=\sum_{p=1}^{19} es^p\cdot ES_p^r(t) \quad (10)$$

Where $ES(t)$ is the energy supply in BTH in year t (en), $ES^r(t)$ (en) is the energy supply in region r in year t, es^p is the standard coal coefficient of energy p, $ES_p^r(t)$ is the physical quantity of energy p in region r in year t (en);

2.3.5 Energy demand

$$ED(t)=\sum_r ED^r=[1 \quad \ldots \quad 1]\begin{bmatrix} \varphi^1 & & \\ & \varphi^2 & \\ & & \varphi^3 \end{bmatrix}\begin{bmatrix} X^1 \\ X^2 \\ X^3 \end{bmatrix}$$
$$+[\omega^1 \quad \omega^2 \quad \omega^3]\begin{bmatrix} PRP^1(t) \\ PRP^2(t) \\ PRP^3(t) \end{bmatrix} \quad (11)$$
$$\varphi^r=[\varphi_1^r \quad \ldots \quad \varphi_{16}^r] \quad (12)$$

where $ED(t)$ is the total energy demand of the BTH region in year t (en); $ED^r(t)$ is the energy demand of r region in year t (en); φ_n^r is the energy consumption intensity of n sector of r region (ex); and θ^r is the energy consumption intensity of residents of r region (ex).

2.3.6 Energy supply and demand balance

The energy supply and demand must not be less than the water demand:

$$ES^r(t) \geq ED^r(t) \quad (13)$$

Table 2. Types of energy consumption

P=1	Raw Coal
P=2	Other Washed Coal
P=3	Briquettes
P=4	Coke
P=5	Coke Oven Gas
P=6	Other Gas
P=7	Other Coking Products
P=8	Crude Oil
P=9	Gasoline
P=10	Kerosene
P=11	Diesel Oil
P=12	Fuel Oil
P=13	LPG
P=14	Refinery Gas
P=15	Other Petroleum Products
P=16	Natural Gas
P=17	Heat
P=18	Electricity
P=19	Other Energy

2.4 Environmental system

2.4.1 Sewage discharge

Sewage is closely connected to water consumption, and the amount of sewage treatment results from industrial development (except for the primary industry) and residents' lives, reflecting the coupling mechanism of the water environment and economic systems.

$$SWG(t) = \sum_r SWG^r(t) = [sdr^1 \quad sdr^2 \quad sdr^3] \begin{bmatrix} WD^1(t) \\ WD^2(t) \\ WD^3(t) \end{bmatrix} \quad (14)$$

$$sdr^r = \frac{SWG^r(2019)}{WD^r(2019)} \quad (15)$$

where $SWG(t)$ is the total amount of sewage discharge of the BTH region in year t (en), $SWG^r(t)$ is the sewage emitted in r region in year t (en), and sdr^r is the rate of sewage emitted in r region in year t (ex).

2.4.2 Reclaimed water production

Reclaimed water production depends on the utilisation rate and the amount of sewage discharged.

$$RW(t) = \sum_r RW^r(t) = [ur^1 \quad ur^2 \quad ur^3] \begin{bmatrix} SWG^1(t) \\ SWG^2(t) \\ SWG^3(t) \end{bmatrix} \quad (16)$$

$$ur^r = \frac{RW^r(2019)}{SWG^r(2019)} \quad (17)$$

where $RW(t)$ is the total amount of reclaimed water in the BTH region in year t (en), and ur^r is the utilisation rate of reclaimed water (ex).

2.4.3 Water pollutants emission

Water pollutant emissions are primarily caused by industrial production and residential living. As agricultural sewage discharges separately, agricultural pollutants are determined by agricultural sector production and emission intensity. As reclaimed water is derived from sewage and reused as a water supply resource, it can contribute to water pollutant reduction.

$$Q_{pollution_l(t)} = \sum_r pollution_l^r(t) + [ei^1_{Agr-pollution_l} \quad ei^2_{Agr-pollution_l} \quad ei^3_{Agr-pollution_l}] \begin{bmatrix} Xn^1_{Agr} \\ Xn^2_{Agr} \\ Xn^3_{Agr} \end{bmatrix} + [ec^1_{pollution_l} \quad ec^2_{pollution_l} \quad ec^3_{pollution_l}] \begin{bmatrix} SWG^1(t) - RW^1(t) \\ SWG^2(t) - RW^2(t) \\ SWG^3(t) - RW^3(t) \end{bmatrix} \quad (18)$$

$$ei^r_{Agr-pollution_l} = \frac{Q_{pollution}{}^r_{l-Agr}(2019)}{Xn^r_{Agr}(2019)} \quad (19)$$

$$ec^r_{pollution_l} = \frac{Q_{pollution}{}^r_{l-ind+living}(2019)}{(SWG^r(2019) - RW^r(2019))} \quad (20)$$

Note that when l =1, it refers to COD emissions, and when l =2, it refers to the NH_3-N emissions.
where $Q_{pollution_l(t)}$ is the total water pollutant emissions of the BTH region in year t (en), $Q_{pollution_l^r(t)}$ is the water pollutant emissions of r region in year t (en), $ei^r_{Agr-pollution_l}$ is the emission intensity of agricultural pollutants (ex), and $ec^r_{pollution_l}$ is the emission concentration of industrial and residential pollutants (ex).

2.4.4 CO_2 emissions

CO_2 emissions primarily caused by the energy consumption of industrial production and residential living:

$$CO_2(t) = \sum_r CO_2^r(t) \quad (21)$$

$$CO_2^r(t) = \sum_{p=1}^{19} cco_p \cdot ED_p(t) - RCO_2(t) \quad (22)$$

$$RCO_2(t) = cco_{18} \cdot ELEC_{reg}(t) \quad (23)$$

where $CO_2(t)$ represents the total CO_2 emissions in year t, $RCO_2(t)$ represents the amount of CO_2 emission reduction in year t which can be expressed as Eq. (15), and cco_p represents the carbon emissions factor of energy p.

3. RESULTS

3.1 Cross-regional synergy affects on carbon peak pathways

Traditional manufacturing industries that achieve cross-regional synergy can still release location advantages without negative environmental impacts. According to the simulation results, industrial synergy optimization among the BTH agglomerations can accelerate achieving carbon peak, while Beijing, Tianjin, and Hebei will reach carbon peak at different times.

3.2 Energy structure adjustment with consideration on regional coordinated development

In addition that clean electrification has obvious stimulating effects on carbon reduction, we can also clarify the transfer-out or transfer-in of energy flow among cross-regional areas. The simulation results indicate that the BTH region can advanced the coordinated development through not only industrial optimization, but also interregional energy distribution. For instance, Hebei can achieve power out to Beijing more reasonably based on the regional electricity network.

3.3 Regional collaborative impact on water-energy nexus

Furthermore, regional collaborative development optimizes the allocation of water resource and energy, and alleviates pollution and CO_2 emissions synergistically. Under dual constraints of carbon emissions and water pollution, the regional carbon peak pathways can also improve water environmental situations, including the water resource distribution and water pollutants reduction.

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DECLARATION OF INTEREST STATEMENT

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

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