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Addressing Resource-Driven Energy Optimization Challenges in Water-Scarce Urban Agglomerations through Game-Theoretic and Multi-Objective Approaches [#]

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ABSTRACT

Ensuring access to affordable energy and water resources is essential for achieving the United Nations Sustainable Development Goals. Urban energy and water systems exhibit strong interconnectivity and interdependence. We adopt a bottom-up, two-tier, multi-stage multi-agent game combined with multi-objective optimization to quantify intra-city energy–water interaction dynamics and determine optimal resource-dominance allocations across the urban cluster. Our results show significant spatial disparities among cities such as Ordos and Yulin, which exhibit energy carbon footprints of approximately 2.46 t CO_2 / tce and water footprints of about 1.52 billion m^3 -- exceeding the regional averages by 39.3% and 21.7%, respectively. Under a shifting resource dominance paradigm, as exemplified by Ordos, the energy-dominant Stackelberg scenario achieves economic benefits 28.5% and 19.7% higher than those of water-dominant and cooperative scenarios. The formation of a coal–coal power to coal-to-chemicals industrial chain that strategic resource coupling can enhance systemic resilience. We also provide recommendations for promoting sustainable urban transitions in resource-constrained regions by strengthening system-level coordination between energy and water subsystems.

Keywords: urban energy–water nexus, urban resilience, life cycle assessment, stackelberg game model, multi-objective optimization

NONMENCLATURE

Abbreviations	
EW Nexus	Energy and water sectors nexus
LCA	Life cycle assessment
TWA	Total water amount
ECA	Energy consumption amount
GHG	Greenhouse gas
CCUS	Carbon capture utility storage
Symbols	
n	Year
e	Energy
w	Water
$W_{blue, direct}$	Blue water footprint
$W_{grey, direct}$	Grey water footprint
L, m, n, b, h_2, c	Water transfer project characters
Q	The volume of water
C	Concentration
E_1	Electricity consumption of water Treatment plants
T	Temperature
μ	Heater power consumption

1. INTRODUCTION

Profound interconnections have formed between human societies and natural resource systems globally. Supply–demand imbalances among countries, cities, and sectors have intensified global supply chains. From 2016 to 2020, China's electricity demand rose 3.6-4.8% per year, worsening energy shortages; water use for energy production is projected to increase 77% by 2030 over 2015, further increasing water-supply uncertainty. Meanwhile, innovations in clean technologies—such as renewables and unconventional water reuse—have improved resource availability but increased the complexity of intercity and intersector coordination, magnifying externalities and driving multi-dimensional changes in the urban energy–water nexus. While the evolution of these systems adheres to clear logical principles, treating energy and water as an integrated system makes their co-evolution and resource restructuring inherently random and hard to manage. Therefore, effectively identifying and quantifying energy-water nexus interactions and examining resource

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structures in energy- or water-dominant cities are essential for developing secure, coordinated, and sustainable nexus strategies.

In real-world settings, the interplay of multiple factors imposes substantial constraints on urban energy and water systems. These constraints primarily manifest as energy consumption in water systems and water use in energy systems. On one hand, water abstraction, conveyance, and wastewater treatment demand substantial energy for pumping, purification, treatment, heating, cooling, and domestic use. Urban water supply systems consume an estimated 2%–8% of global energy. On the other hand, energy production, consumption, and distribution also demand large volumes of water, since the coal-to-power supply chain depends on water for purification and cooling. Overall, water-scarce cities face intensified energy–water conflicts, making nexus issue identification crucial for informed decision-making and sustainable development.

1.1 Literature review

The interplay between urban energy and water systems has always involved intricate competition and trade-offs; in 2008, the World Economic Forum redefined the "energy–water nexus," moving away from a sectoral view toward holistic integration. Existing research primarily employs top-down approaches to assess complex resource flows between urban energy and water sectors. Researchers apply life cycle assessment to analyze trade-offs between urban water demand and energy use. Network analysis integrates material flows, water-use parameters, and resource constraints to quantify coupling in urban energy–water systems[1]. When data availability is limited, various input–output models quantify direct and indirect energy–water flows in cities[2]. Alternatively, general equilibrium and system dynamics models simulate inter-sector energy–water exchange pathways across cities. However, most research treats energy and water sectors as a homogeneous group and analyzes aggregate distributions. To capture individual decision-making in urban energy–water systems, integrated multi-model approaches combining systems thinking and mathematical modeling are needed to analyze hidden inter-system layers and resource-use intensities, clarify efficiency, and optimize allocation.

Research on the energy–water nexus now focuses primarily on the urban scale. Urban energy and water sectors meet social and ecological demands but inevitably cause pollution and resource overuse. To alleviate inter-sector conflicts, cross-departmental and cross-regional collaboration has become central to focus in nexus research[3]. Researchers use various spatiotemporal statistical methods to evaluate supply–demand matching and resource optimization across urban energy–water sectors[4]. Urban metabolic network analyses map energy and water flows across sectors and employ multi-objective optimization (e.g., NSGA-II) and game theory to address energy–water imbalances[5]. Water footprints of energy consumption and energy footprints of water use are quantified for multiple cities from supply- and demand-side perspectives.

Incorporating uncertainty theory, ideal generation mixes are derived within defined uncertainty bounds to optimize performance and cost, balance economic and sustainability objectives, and identify optimal urban development pathways. To meet its 2025 carbon peak and 2030 neutrality goals, China has implemented CCUS measures—including carbon capture, sequestration, and storage—that will significantly transform future urban energy–water systems. Consequently, examining future uncertainties in the urban-cluster energy–water nexus and optimizing resource distribution have become vital strategies.

1.2 Objective and contributions

We propose a bottom-up, two-tier, multi-stage, multi-agent game coupled with multi-objective optimization to quantify the interactive evolution of energy–water systems within the 19 water-scarce, energy-rich cities of the Yellow River Ji-shaped meander, the intercity resource flows, and the optimal energy–water allocation under future uncertainty scenarios. This study makes three key contributions (see Fig. 1).

(1) We perform multi-temporal rolling simulations at both the city and cluster levels to identify the evolution pathways of the internal energy–water nexus in each city and the shifts in resource dominance across the urban cluster.

(2) Treating energy and water sectors as independent agents within each city, we apply three game theory strategies, introduce uncertainty factors starting from historical phases, and simulate optimal future configurations.

(3) Each urban cluster acts as a distinct agent: building on optimal strategy classifications from the city level, we use distributed solution methods across various

uncertainty scenarios to identify resource dominance categories and optimize resource distribution within the cluster.

2. STUDY AREA AND METHODS

2.1 Section of EW nexus theory

The Yellow River "Ji" urban cluster hosts five key energy sectors—coal, petrochemicals, oil & gas, thermal power, and hydrogen—that supply urban areas with heat, power, gas, and associated chemical products. This study initially examines supply–demand dynamics in traditional industries—coal mining, petrochemicals, oil & gas extraction, and thermal power—and incorporates emerging industries like hydrogen, solar PV, and wind power for future scenarios. In modeling, energy and water departments act as two agents whose interactions under resource constraints yield equilibrium solutions for each city under cooperative, non-cooperative, and hybrid scenarios, optimized for urban benefit and environmental impact. These optimal strategies are then applied at the city level, where each city is defined by its own utility function and fuzzy indicators that delineate its decision space. We employ robust NSGA-II algorithm to generate optimal configurations that maximize utility,

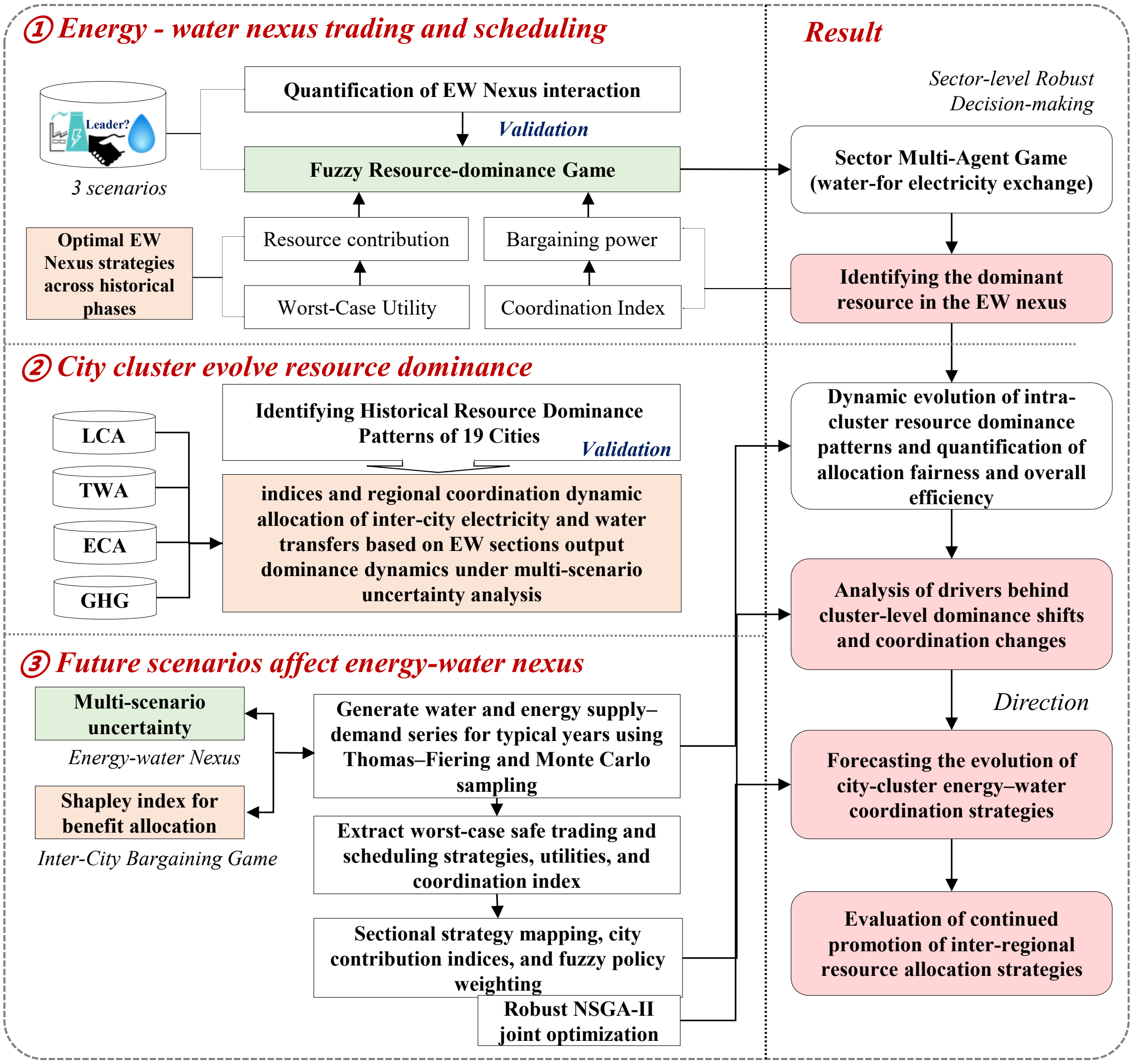

Fig. 1 Research Framework

Occupying less than 4% of China's land area, the Yellow River "Ji" city cluster provides nearly half of the nation's energy output and reserves, acting as a stabilizer for the national energy supply. Proven coal reserves here comprise over 50% of the national total, and fossil fuel reserves exceed 2 trillion tonnes of standard coal. The region also offers substantial potential for wind, solar, and hydrogen energy. Specifically, Ordos (Inner Mongolia), Yulin (Shaanxi), and Ningdong (Ningxia) form China's energy–petrochemical "Golden Triangle." However, the region's per capita water availability is only 338 m³, roughly 17% of the national average. Water scarcity constitutes the main bottleneck to the strategic economic development of the Yellow River "Ji" region.

spanning three historical stages (2010, 2015, 2020) and three future scenarios (2025, 2030, 2050).

In real energy–water nexus systems, variations in resources, policies, and economic conditions create substantial heterogeneity and uncertainty in cities' strategic choices. We develop mixed-strategy and evolutionary game models using each agent's utility function and account for spatial differences among cities. This framework quantifies strategic uncertainty in energy system optimization and reveals how coordination and resilience evolve under different strategy mixes.

Beyond accurately characterizing future scenarios, uncertainty is also critical to model validity. In the core energy–water nexus model of this study, uncertainty comprises five main dimensions: (1) We employ asymmetric-information game theory to quantify uncertainty stemming from incomplete information in decision-making by energy and water stakeholders. (2) Based on demand elasticity theory and uncertainty analysis, we define high, medium, and low demand scenarios to quantify demand-side uncertainty due to population growth, industrial shifts, and economic growth. (3) Combining stochastic hydrological sequence simulation with the Thomas–Fiering model and Monte Carlo uncertainty sampling, we generate uncertain water-supply series under varying hydrological conditions. (4) We apply random-parameter and scenario simulations to establish fluctuation ranges and probability distributions for energy and water prices, directly representing the demand-side uncertainty in item 2. (5) Policy uncertainty is addressed by simulating multiple government decision-making scenarios.

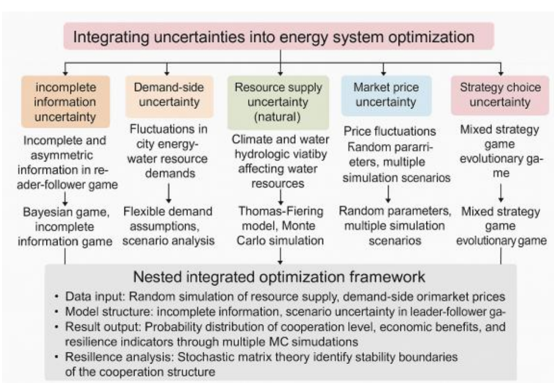

Fig. 2 Uncertainty Framework for the multi-tier EW nexus

2.2 Section of EW nexus optimal methods

2.2.1 Energy section for water

Energy extraction and its subsequent utilization processes almost always require significant water resources. Calculation of the energy water footprint (W_E) includes two components: direct water footprint and indirect water footprint. Direct water footprint(W_{direct}) refers to the actual water used during energy production, and indirect water footprint ($W_{indirect}$) represents the water embodied in the materials consumed in that process. The direct and indirect water footprints are assessed in terms of blue and grey water. Blue water footprint ($W_{blue, direct}$) indicates the consumption of surface and groundwater in energy production, while grey water footprint($W_{grey, direct}$) is the freshwater volume required to dilute and assimilate the pollutants released.

$$W_{EN}=W_{direct}+W_{indirect}$$
$$=W_{blue,direct}+W_{grey,direct}+W_{blue,indirect}+W_{grey,indirect} \quad (1)$$

$$W_{EN}=\sum_{i=1}^{n}(W_{i(blue,direct)}+W_{i(grey,direct)})$$
$$+\sum_{i=1}^{n}(W_{i(blue,indirect)}+W_{i(grey,indirect)}) \quad (2)$$

$$W_{blue,\ direct}= W_i^C+W_i^o+W_i^G+W_i^T= Q_i^b+Q_i^{ind}+Q_i^c+Q_i^u \quad (3)$$

$$W_{grey,\ direct}= G / (C_{max}\text{-}C_{nat})= (L \times V_p) / (C_{max}\text{-}C_{nat}) \quad (4)$$

Here, i denotes the energy type, specifically coal, petroleum, natural gas, and coal-fired power generation. Coal's footprint covers water used in extraction and in the coal washing and preparation stages. Q_i^b, Q_i^{ind}, Q_i^c, Q_i^u encompasses water incorporated into produced or imported goods, industrial process water, utility water, and reclaimed water. G represents pollutants emitted per unit energy produced (g/GJ); L denotes wastewater discharge per unit energy production (m/GJ); V_p represents contaminant concentration in the wastewater (mg/m), C_{max} is the maximum allowable pollutant concentration under water quality standards (mg/m³) ; C_{nat} refers to the initial concentration of pollutants in the receiving water (mg/m³), taken as zero in this study.

2.2.2 Water section for energy

Energy is consumed in the social water cycle when humans intervene to meet demands, specifically during water withdrawal, supply, utilization, and discharge operations.

Water abstraction, whether from surface sources or aquifers, invariably involves energy expenditure. Surface water withdrawal comprises four types of infrastructure: impoundment in reservoirs or tanks; diversion from rivers or reservoirs; pumping to elevate water to required locations; and inter-basin transfer through dedicated conveyance systems.

$$WE_{total} = WE_{up} + WE_{trans} + WE_{pump} \quad (5)$$

$$WE_{up} = (mgh_1) / (3.6\times 10^6 \times \varepsilon) \quad (6)$$

$$WE_{trans} = Lm^2n^2(b+2h_2\sqrt{1+c^2})^{\frac{4}{3}} / [(b+ch)\times h_2]^{10/3} \quad (7)$$

$$WE_{pump} = (0.00273Vh_3) / (\delta(1-\theta)) \quad (8)$$

WE_{up}, WE_{trans}, WE_{pump} refer to energy used in surface water lifting, surface water conveyance, and groundwater extraction (kW·h); m, g denote transported water mass (kg) and gravitational acceleration (N/kg); h_1 indicates the elevation head (m); ε denotes pump efficiency (diesel≈15%, electric≈40%); L, m, n, b, h_2, c, are the conveyance channel coefficients; V is the water volume pumped, m; h_3 is the pumping head (m); δ represents pumping equipment efficiency (electric well≈40%, diesel pump≈15%); θ is power transmission loss (≈7%).

Water supply encompasses production and distribution stages; production involves treatment processes such as clarification, disinfection, deodorization, decolorization, and softening at water treatment plants. Water distribution covers pipeline networks from source to end-users, typically including pumping stations, main transmission pipelines, distribution networks, and regulating structures. Energy use in water supply systems consists of production and distribution consumption; production energy can be subdivided by source into conventional treatment, seawater desalination, and reclaimed water processing.

$$WE_s = k_{cw}\cdot W_{cw} + WE_{dw} + WE_{rw} \quad (9)$$

$$k_{cw} = (E_1+E_2+\cdots E_n)/(W_1+W_2+\cdots W_n) \quad (10)$$

k_{cw} is the mean specific energy use of standard water treatment facilities (kwh/m³), E_1, E_2…E_n are each plant's yearly power consumption (kwh), W_1, W_2…W_n their annual output (m³). WE_s, WE_{cw}, WE_{dw}, WE_{rw} indicate the energy required for water delivery, conventional treatment, desalination, and water reuse processes (kW·h).

Domestic water energy use is categorized into thermal and mechanical consumption: thermal energy heats water for drinking, cooking, and bathing, while mechanical energy powers water appliances (e.g., washing machines) via motors.

$$WE_u = W_{hw} + WE_{pw} + WE_{iw} \quad (11)$$

$$E_h = ([V\rho c(T_t - T_i)]/\mu + E)/(Q\times 3.6\times 10^3) \quad (12)$$

$$E_l = (B\times D\times 3.6\times 10^3)/(B\times D\times 3.6\times 10^3) \quad (13)$$

Drainage refers primarily to the stages of wastewater collection, transport, purification, and release. Reclaimed water energy consumption is largely determined by local treatment technologies and influenced by wastewater composition complexity and end-use applications. Drainage system energy use is primarily affected by pump head, sewage conveyance distance, and pipeline slope.

$$H = L\times\theta \quad (14)$$

$$WE_s = (H\times M)/n \quad (15)$$

H represents pump head (m); L denotes the straight-line distance before and after sewage lifting (m); θ is the average slope of the sewer network, typically set at 1%. WE_s is the energy used for wastewater lifting (kwh), M indicates the pumped wastewater volume (m³), n is the average pump efficiency (%), typically 0.75.

2.2.4 EW nexus multi-agent game assess interaction

Based on the described energy–water interactions, we derive baseline input data ranges (maximum and minimum) for the representative years 2010, 2015, and 2020. Subsequently, the city's benefit function is formulated as an inverted-U of energy and water use; the grey water footprint denotes environmental impact, the blue water footprint embodies resource limitation, and energy consumption for reclaimed water quantifies environmental welfare. Under this scenario, using 2010 as the reference, we compute contribution indices for the energy and water departments as agents, then perform a multi-stage fuzzy-optimal game based on allocation ratios to determine the optimal energy–water usage.

2.2.5 Urban multi-agent game for the optimal strategy

Each city's chosen optimal strategy in the energy–water domain is fed in as a node, with every city acting as an agent to request or cede resources. We iteratively adjust city utility functions, employ Shapley value metrics to assess distribution equity, perform sensitivity analysis, and model the energy–water coordination performance of the urban cluster in both existing and prospective contexts.

$$U_i(s_i, s_{i-1}, R_i, w_i) = \alpha_i(B_i(s_i)) - \beta_i(C_i(s_i)) + \gamma_i \sum_{j\neq i} \min\{s_i, s_{ij}\} \quad (16)$$

3. RESULTS AND DISCUSSION

3.1 Evolution of intra-city energy-water nexus interaction intensity

The energy–water nexus within the Yellow River "Ji" urban cluster exhibits high interaction intensity, although the dominant resource types vary among cities. Energy-rich cities such as Ordos, Yulin, and Zhongwei have an average carbon footprint of 2.46 t CO_2 per tce, approximately 40 % above the regional mean, whereas water-rich cities like Xi'an and Weinan exhibit an average water footprint of 1.13 billion m^3, about 32 % higher than average.

3.2 Resource allocation dynamic in urban clusters

Simulations show that in water-dominated scenarios, energy-rich cities lose up to 65 % of economic benefit to optimize blue and green water footprints. For example, Ordos's output falls to 35 % of its baseline. Conversely, in an energy-dominated game, water extraction intensity rises by 66 % relative to the initial stage to sustain development. Therefore, to address future uncertainties, cooperative game models are preferable in highly energy-endowed regions.

3.3 Optimal coordination pathway for urban clusters under uncertainty scenarios

In future scenarios, natural condition shifts will slightly rebound blue water footprints, but rising market prices make energy-dominant Stackelberg games more favorable for moderately energy-rich cities, whereas less energy-rich cities are best served by water-dominant Stackelberg frameworks. Moreover, to support the development of neighboring cities, supply from highly energy-rich centers will continue to climb, and intercity resource exchanges will significantly advance the regional energy–water system.

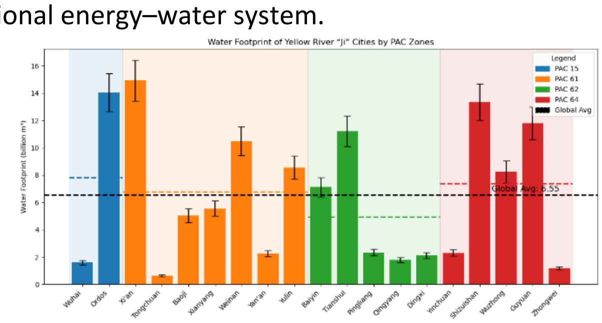

Fig. 3 Water footprint evolution in the different regions

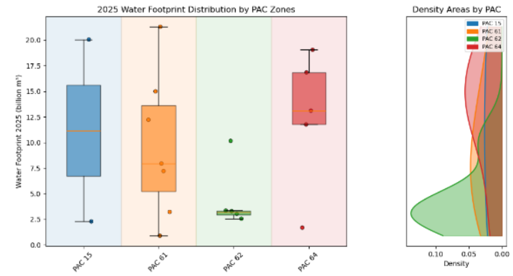

Fig. 4 Water footprint evolution in the optimal scenario

4. CONCLUSIONS

We propose a bottom-up, two-tier, multi-stage, multi-agent game coupled to quantify energy–water nexus interactions within each of the 19 Yellow River cities and to map the coordinated development trajectories of the cluster's energy–water system. By integrating robust NSGA-II for joint simulation of urban energy structure configurations, we find that in future scenarios highly energy-rich cities maximize energy–water nexus cohesion by adopting energy-led Stackelberg games and reallocating energy to less endowed cities.

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