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LEAP-WEAP analysis of urban energy-water dynamic nexus in Beijing (China)

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ABSTRACT

Based on LEAP and WEAP, this paper establishes the coupled model of energy and water in cities. With Beijing as a case, 26 scenarios are designed to explore the energy saving/water saving of different policies in Beijing in the future and its nexus effect, including the sensitivity analysis of the results. The results show that the total energy consumption in Beijing will grow slowly by year. Carbon emissions will peak in 2020, and fluctuate after 2035 it will slowly increase until 2050. Total water demand is stable between 3.6 and 4.1 billion cubic meters. According to the forecasted water supply capacity, there is no shortage of water supply and demand. The proportion of groundwater from the source of water supply fell to 27%, and the proportion of water in the South-to-North Water Transfer increased to 40%. The total energy saving of the "13th Five-Year Plan" water saving policy is 1.003 million tons of standard coal, which is equivalent to 8.165 billion kWh of electricity. The energy saving policy has reached 276 million cubic meters of water, equivalent to 140 Kunming Lakes. The energy demand of residents' lives, service industry, construction industry and traditional manufacturing industry has a good correlation with water demand value, which proved they are important water-coupled sectors. In terms of energy-saving/water-saving effects in different scenarios and recent/long range periods, the industrial structure optimization policy showed good energy-saving potential in the short-term, but the long-term energy-saving effect was not obvious, while it was accompanied by an increase in water consumption. The irrigation technology innovation and planting structure optimization scenarios in the agricultural sector have better energy saving and water saving effects in the short term. However, with the occurrence and further expansion of water shortage, the medium and long term the water saving effect is sill, while the energy saving effect is not significant. The sensitivity analysis shows that the parameters of the scenario such as economic slowdown, industrial structure optimization, development of public transportation, and planting structure optimization are more sensitive. For the synergistic effect of water and energy conservation, the synergy effect is more obvious in the energy saving scenarios of the service industry and the industrial sector. For the policies of the same department, the synergistic saving effect of the situation of improving energy intensity is obvious. From the perspective of the difficulty in policy implementation process and overview effects, the water saving and energy saving policies of the industrial sector face more difficulties while implementation. The external power regulation policy and the capital rising residents' wareness of water saving policy has good performance both in the difficulty of implementation and overview effects.

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1. Introduction

The International Energy Agency (IEA) emphasized the significance of the energy-water relationship with respect to sustainable development. In the 2016 World Energy Outlook, it was stressed the interdependency between energy and water. A consistent management of energy and water would be especially desirable for cities, where population and industry are highly concentrated. In fact, if the interactions between the two resources are not considered, many unexpected side effects might occur. For example, according to Tang and Qu [1]; 6–10 L of water are consumed to produce 1 m^3 of coal gas. Thus, the annual production of 2 billion m^3 of coal gas consumes up to 25 million tons of water. Instead, the introduction of policy and management actions informed by an appropriate modeling of resources nexus, could partially avoid a higher consumption of resources and reduce the impacts on the environment.

Based on past experience, savings of both energy and water are possible. In the case of cities, the industry sector is especially relevant for such a purpose. According to Gu and Teng [2]; the application of the Eleventh Five-Year Plan, detailing a list of energy-saving measures, as well as investments in energy conservation and emissions reduction, generated a beneficial impact on both resources. For major industrial sectors, the energy saved was up to 9.2% of the national total energy consumption. At the same time, 2.81% of water was directly saved and 2.45% of the full water life cycle was conserved. The same study, however, highlighted the differences among different industry sectors. For the building materials sector, energy-saving policies saved 20.45% of energy and 15.91% of water. For the light industry sector, up to 23.65% of energy was conserved while only 1.83% of water was saved. On the other side, water-saving actions and policies are effective in reducing the consumption of energy. According to Wang et al. [3]; a change in design of a coke quenching plant reduced the water consumption from 9.03 m^3 to 3.21 m^3 for processing a ton of fuel. Hence, approximately 6 million m^3 of water and 2 million kWh of electricity were saved annually with an operation cost of 3 million CNY saved each year. For the urban agricultural sector, According to the study conducted on Beijing by Liang and Wang [4]; the introduction of drip irrigation generated a relevant energy saving of 71,042.5 kWh, equal to 1.713% of the total electricity consumption of Beijing during the year of study.

Focusing on larger cities and considering the United Nations World Urbanization Prospects 2018 [5], Beijing is one of the eight largest cities of the world, with a population of 21,707,000 permanent residents. As for other big cities, Beijing is facing a severe situation in terms of high energy and water consumption rates. Because of population growth and industrial expansion, demands for energy and water in Beijing are increasing. Supplies of both energy and water resources heavily rely on imports. In 2017, external electricity accounted for 26% of the city's energy consumption, while 22% of the total water supply was from the South-North Water Transfer Project [6]. Meanwhile, the groundwater level has not yet recovered and the overexploitation situation has not yet been completely alleviated.

Further, although constraints on energy and water consumption were set in the Twelfth and Thirteenth Five-Year Plans of Beijing, these goals did not consider the close relationship between energy and water. In addition, situations such as contradictory goals and failures exist during water-saving policy-making and implementation. Besides, energy master plans do not sufficiently consider water resource constraints and they may contradict the "three red lines" of industrial water consumption [7]. At present, water-saving measures in Beijing are mostly driven by administrative acts instead than process and technological improvements. Examples are water consumption planning and the issuance of water withdrawal permits. Even if the residents awareness increased, their engagement is still too low [8]. After Phase I of the South-North Water Transfer (Middle Route) Project, some media suggested that water from the South should not be wasted in the North, emphasizing that the project alleviated water supply pressures in the short-term. In the meantime, the South-North Water Transfer Project influenced, to a certain degree, the water supply patterns in Beijing, impacting on the original water resource system. The long-term effects are still unknown and further research on subsequent resource allocation and management is also necessary [9]. In the future, the operation of a new airport and the organization of large-scale events, such as the Winter Olympic Games, together with the decentralization and industry relocation, will further modify the water and energy consumption patterns in Beijing. The ability to supply energy and water resources will further affect the future development of the city. In addition, the demand and supply of energy and water are closely associated.

To realize the sustainable development of energy and water resources in Beijing, we need to understand their relationships and seek ways for joint development. Based on the above analysis, we proposed an analytical framework for energy and water coupling through long-range energy alternatives planning (LEAP) and water evaluation and planning (WEAP), to derive specific policies and plans for an integrated management of energy and water at urban level. We chose Beijing as a case, due to its population size and its severe water and energy constraints. Compared with other models, the proposed framework includes energy-water resource couplings. For example, the specification of energy and water resources used in the process of water extraction, transportation and supply. In the scenario setting, we considered the consequences of energy saving and water saving policies at sectorial level, as well as specific requirements, that are necessary for a mega-city.

2. Method

2.1. Literature review

The investigation of multiple energy-water relationships has become a hot research topic, being critical for a future global sustainable. Current research on energy and water nexus systems includes detailed descriptions of the complex relationships between the two resources and the models used to describe them.

The relation between water and energy were investigated in several researches. Wakeel et al. [10] and Gu et al. [11] provided detailed reviews on this topic. These inter-relations were considered at different scales: national [12,13]; regional [14–16]; urban [17–21]. Such a relation was also investigated for specific sectors or processes [22–27]. Quantification of such relations were presented in several works [28–30], analyzing the spatial and temporal energy consumption patterns of the urban water supply system.

Such methods can be expanded to include dynamic scenario predictions. This is especially useful for decision managers, in order to design long-term efficient energy and water consumption systems [31]. At present, there are several dynamic modeling methods applied to urban energy-water nexus research. They include system dynamics models [32], computable general equilibrium models [33,34], modified energy models, such as MARKAL/TIMES, MESSAGE and PRIMA [35] and modified water models, like AQUATOOL [36].

In some studies, LEAP and WEAP models were adopted to look into energy-water nexus at project, sector, urban and regional scales. The literature prevalently focused on project and sector levels, while there are fewer studies at the city level. The Stockholm Environment Institute, which developed both models, employed them in real planning, including seawater desalination and regional water pipeline construction. These models are based on the mass balance principle. They can consider energy and water resource configurations from both demand and supply perspectives, at the same time. They are also equipped with scenario analysis tools. The impact of the developed solutions on energy consumption, water resources and regional greenhouse gas emissions were also examined [37]. Based on the LEAP-WEAP model, Agrawal et al. [38] constructed a water consumption and greenhouse gas emission assessment for the power section in Alberta, Western Canada and provided the greenhouse gas saving potentials, water consumption, and greenhouse gas emission reduction costs under nine scenarios. Lin et al. [39] crated a LEAP-WEAP model for energy-water nexus utilization at the city level. Using Xiamen city as an example, they designed 11 scenarios and discussed the influences of various demand and supply factors on urban energy-water nexus relationships. Previously, Li [40] employed the LEAP-WEAP model to examine the energy-water relationship in a case study on Ningxia. He estimated the water consumption used by energy systems and the energy consumptions during water resource utilization. He divided Ningxia into five prefectural-level regions and constructed WEAP and LEAP models separately for each region. Quantitative calculations derived from the models, showed that energy systems in Ningxia will face critical water resource shortages in future few years, indicating some improvements in the energy and water systems interactions. Based on the LEAP-WEAP model, Pan Pan [41] discussed the energy-water nexus relationships of the power sectors in the Beijing-Tianjin-Hebei region under two climate scenarios and three development scenarios. He also analyzed the potentials of energy structure adjustments and technological advancement in alleviating pressures on regional water resources and promoting sustainable development.

Compared to other models, the LEAP-WEAP model provides certain advantages for studying energy-water nexus relationships at the city level. Compared to other dynamic models, WEAP has powerful built-in hydrological analysis tools for water supply simulation, being capable of simulating fine details such as river runoff, water intake points and water transfer distances. Compared to computable general equilibrium models, WEAP models are user-friendly and have simpler operation procedures. Unlike modified energy and water models, the LEAP-WEAP models have built-in data transmission functions, so that core parameters and energy and water simulation results can be shared, facilitating nexus analyses. However, the set-up of a LEAP-WEAP model requires a higher level of detail with respect to other ones. First, for sector settings in each model, we need detailed data such as activity levels, water or energy consumptions, generator capacities, transformation efficiencies, hydrological runoffs, and infiltration rates of sectors. After that, the LEAP-WEAP model correlates the energy and water resources in each model. The two models will not affect each other when they are running. Instead, the calculation results obtained separately by the two models are exchanged and used as input into the overall model. Thus, they need to run several times to obtain the final results. Lastly, for scenario settings, compared to computable general equilibrium models, it is more difficult for the LEAP-WEAP model to consider economic energy-saving or emission reduction measures such as carbon tax and emissions trading.

In the previous applications of LEAP-WEAP model, the setting of each scenario was often based on literature reviews by the authors and their own assumptions. The types of scenarios can be summarized as follows: (1) Economic development: Different economic growth rates and different industrial structures are set; (2) Technological advancement: This is mainly reflected in consumption reduction, for example, decreased water or energy consumptions alone and simultaneous reduction of the both; (3) Climate change models: Various models, including RCP4.5 and RCP8.5, are used. They mainly affect the entire system by influencing the water supply in the WEAP model; (4) Energy structure changes: These include developments of nuclear energy, biomass energy, hydropower, and natural gas; and (5) Water supply priority changes: The authors can give priority to the use of local water resources over that of imported water resources and vice versa. Similarly, surface water or groundwater resources can be used before the exploitation of the other one. Planning and government documents can also be used as reference.

2.2. Boundary and temporal scale of the model

In this paper, we assumed that the energy (or water) demand of the city is balanced by supply within city boundaries and cross-border resource supplies. Only direct energy (or water) consumption was included in the reference scenario, while water (or energy) consumption by long-distance power transmission (or water transfer across river basins) is not considered. Our boundary setting was similar to Sun et al. [42] and Lin et al. [39]. The spatial distribution of energy (water) demand and supply was not specifically considered, while the energy and water system were divided into different sectors within the existing administrative boundaries.

Considering the need of using the same initial time for energy and water data, year 2015 was selected as reference to predict the medium- and long-term energy and water utilization and their nexus relationships in Beijing from 2015 to 2050, since previous data on. Past works included both medium-term and long-term choice of temporal scale [38, 39]. For this study, based on the actual conditions in Beijing, the use of year 2050 as reference target in many plans, such as *The Beijing Master Plan*, was considered.

LEAP model was used here to predict energy demands. LEAP includes four modules, namely key assumptions, demands, transformations, and resources. The demand and transformation modules are the key ones. WEAP model was applied to predict urban water supply and demand under various scenarios. The models' detailed parameters could be found in Appendix 1 and 2.

2.3. Framework for energy-water nexus analyses

In this study, the sector settings for LEAP and WEAP was included in the analysis framework of the energy-water nexus model, as shown in Fig. 1. The framework contains both the supply and demand sides of energy and water systems, as well as the links between the two systems. Both energy and water systems include seven end-use demands: agricultural, manufacture, power supply sector, water supply sector tertiary industrial, household and construction industrial.

When linking LEAP to WEAP, the water consumption of the energy transformation module is important, especially for the water use in the process of energy production and supply. Power generation demands for different power generation methods were calculated using the energy structure prediction results from LEAP. In the coupled model, the demands were used as input into the WEAP model, to predict the water consumption for various primary energy transformations. Research by Jiang [43] provided reference values for these parameters. Thus, the corresponding descriptions of water and energy resources made by WEAP and LEAP can be linked successfully and the interactions between energy and water systems can be simulated. Similarly, while connecting WEAP to LEAP, we considered the energy consumption during water withdrawal, purification and supply and sewage treatment. The energy consumption of the water supply sector and the domestic water use, such as bathing and cooking, were also considered in this part. In the WEAP model, the total water supply is predicted. According to the prediction result, the energy consumption during water withdrawal, transport, and treatment were estimated. Reference values of energy consumption are available for different components of the water supply [43]. These linkages are summarized by the process represented in Fig. 2.

Referring to Lin et al. [39] study, we also divided connections into two categories: (1) The "interactive link", representing the use of one resource to produce another resource's services, such as energy for water treatment and water for thermal power cooling, and mainly occurs on the supply side; (2) The "connected link", representing water and energy resources, that are connected in devices, whose final purpose is to provide other services, such as water heating and clothes washing, mainly occurring on the demand side.

With respect to the spatial scale, the model does not consider the spatial distribution of energy (water) supply and demand nodes, but only sets up the correlation between different departments in the two models. With respect to the temporal scale, the step size and the data transmission temporal scale for the model is one year, regardless of the

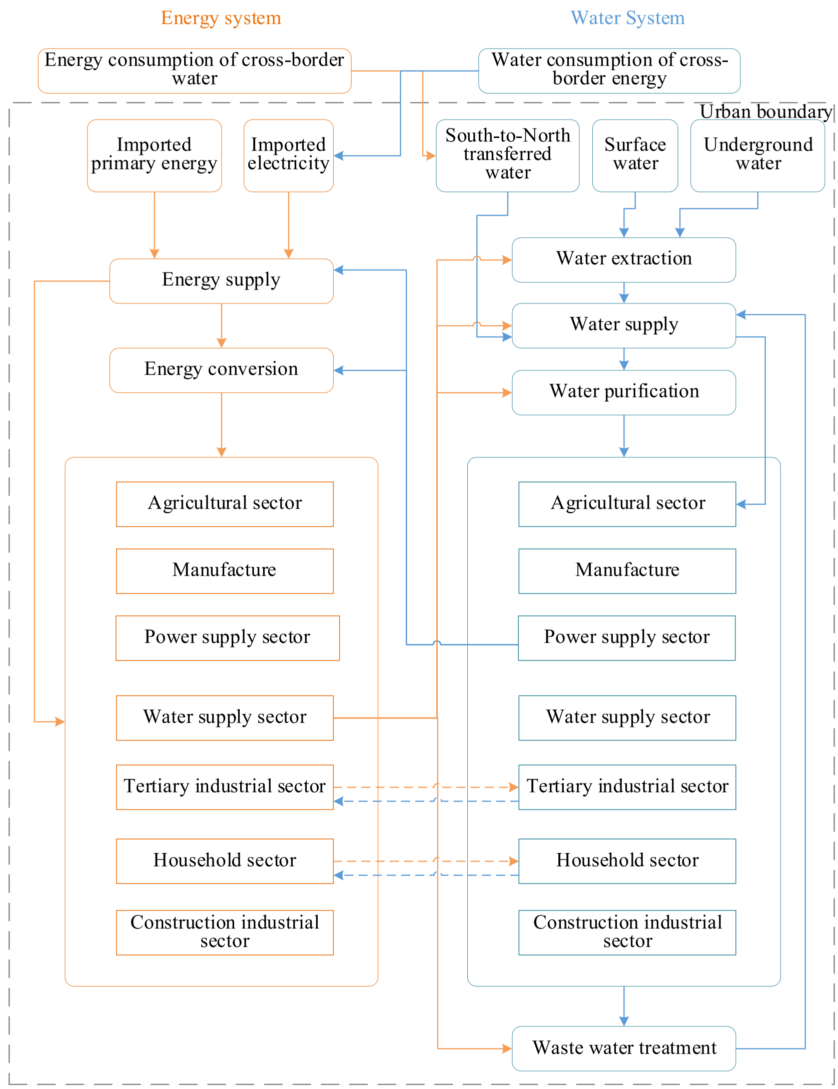

Fig. 1. Energy-water nexus model framework.

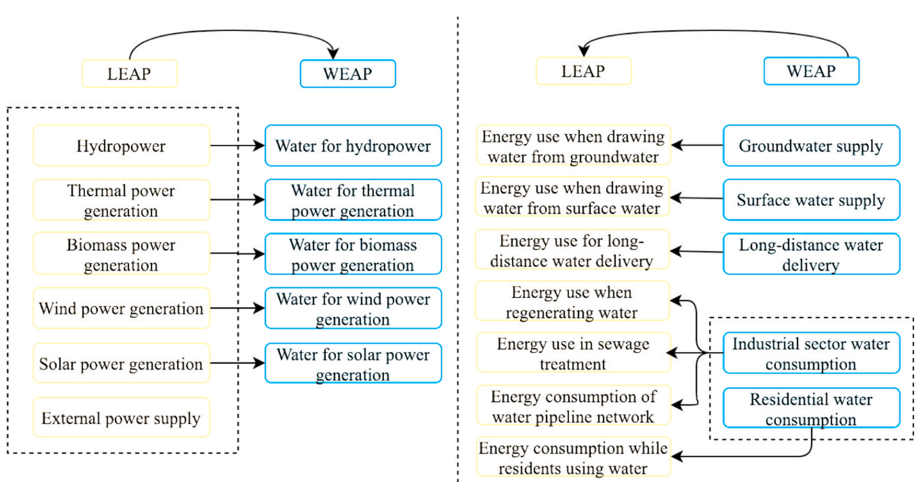

Fig. 2. Water and energy networks of LEAP-WEAP model.

changes within such a time interval. The basic details for software basic of the linkage could be found in Appendix 3.

2.4. Scenario setting

To design the different scenarios for the analysis, business-*as*-usual (BAU) scenarios were first created in LEAP and WEAP separately. They were set according to the activity levels determined by core parameters and extrapolation, based on the current consumption levels without any interventions (See Fig. 3). Based on the BAU scenarios, 23 sub-scenarios were constructed. Each of them represented the energy- and water-saving performances and the joint effects of one single policy. Sub-scenarios of the six sectors were integrated to generate BAU scenario in LEAP and WEAP separately, in order to simulate the most realistic situation. Meanwhile, based on current groundwater overexploitation in Beijing, two water supply scenarios were defined. They were: (1) Restricted groundwater exploitation; (2) Increased utilization of urban reclaimed water. At the moment, in Beijing, a new airport is under construction, while large-scale events, such as the Winter Olympic Games, are planned in the near future. The proposed method considered all these factors, predicting the energy and water demands under these scenarios. The detailed parameters for the scenarios could be found in Appendix 3.

2.5. Sensitivity analysis

We used one-variable-at-a-time approach (OAT) for sensitivity analysis and testing, being widely applied for environmental systems models [44]. This method supports the identification of important synergistic policies, being simple and useable for LEAP-WEAP model. To determine the sensitivity of each parameter, result variation ratios were employed. If an increasing or decreasing by 10% the value of a parameter caused the final amount of energy/water saved to change by more than 10%, the parameter was considered to be sensitive and vice versa.

To conduct a sensitivity analysis, we set three extent of each scenario, divided into three types. Type B scenarios were set as reference, being based on the existing planning documents. Type A scenarios were constructed by increasing the parameter values by 10%, whereas Type C scenarios were created by decreasing the values by 10%. The results in Types A and C scenarios were considered to reflect the sensitivities of the parameters.

Sensitivity index, Ω, was defined as the ratio of the percentage variation of the final result to that of the parameter (10%). The sensitivity indices of Types A and C scenarios are Ω_A and Ω_C, respectively.

$$\Omega_A = \frac{Energy/water\,saving\,ratio\,in\,level\,A - Energy/water\,saving\,ratio\,in\,level\,B}{(Energy/water\,saving\,ratio\,in\,level\,B)*10\%} \tag{1}$$

$$\Omega_C = \frac{Energy/water\,saving\,ratio\,in\,level\,C - Energy/water\,saving\,ratio\,in\,level\,B}{(Energy/water\,saving\,ratio\,in\,level\,B)*10\%} \tag{2}$$

when the sensitivity index Ω_A is less than 1, Ω_C is greater than 1, which is to think the situation under control of parameters with high sensitivity.

3. Results

3.1. Energy and water consumption in Beijing under reference scenarios

3.1.1. Energy demand

In the simulated reference scenarios, the total energy consumption in Beijing gradually increased from 2015 to 2050. The structural variation in energy demands by sectors was not distinct. The total energy demand increased by 2.3% on average from 2015 to 2021, becoming less than 1% after 2021. In terms of sector structure, the proportion of the energy demand for the tertiary sector grew with respect to the total energy demand. In 2025, the simulation results accounted for 35.4% of the total energy demand. The household energy demand remained at 13.25 million tons of standard coal. Projects, such as the construction of the

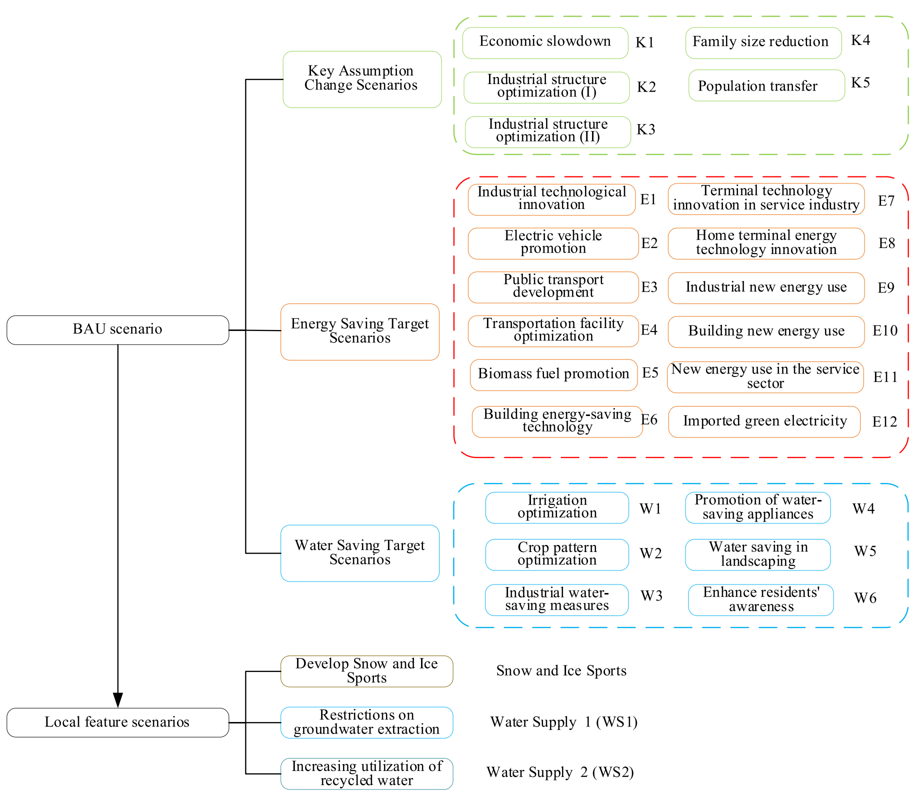

Fig. 3. Structure of scenarios set for this study.

new airport and the organization of the Winter Olympic Games, generated an increase of the total energy demand by 5%–6% for each year. The operation, after the construction of the new airport and the development of the snow sports brought by the Winter Olympics, continued to generate a growth of energy demand. In the family size reduction reference sub-scenario, the household energy demand increased by 1.60 million tons of standard coal in 2050, compared to that in the reference scenario. This accounted for 1.72% of the total energy demand.

Water consumption-related energy demands included those in water withdrawal, supply and transportation, and household water consumption activities. In the simulation, for 2050, this demand equaled 7.12 million tons of standard coal in total. During the prediction period (2015–2050), it accounted, on average, for 7.74% of the total energy demand. More specifically, the energy consumption in household water consumption activities, water withdrawal, water production, water transportation, sewage treatment, and sewage recycling accounted for 14.48%, 45.48%, 4.15%, 12.43%, 2.41%, and 21.05% of the total water consumption-related energy demand, respectively.

3.1.2. Energy structure by types

An analysis on the energy structure showed that the energy contribution by fossil fuels will be reduced (see Fig. 4). In particular, the energy contribution by coal dropped from 7.67% in 2015 to 1.11% in 2050. Meanwhile, the contribution by renewable energy sources increased. The contribution from electricity grew from 23% in 2015 to 25.81% in 2050. This energy component refers to the externally transferred power. This fact implies that Beijing will rely more on secondary energy input from outside.

3.1.3. Carbon emissions

In the simulation related to the reference scenario, the carbon emissions in Beijing peaked in 2020 and then fluctuated after 2035. The carbon emissions increased from 74.88 million tons in 2035 to 76.30 million tons in 2050. This increase is equivalent to 1.422 million tons of carbon dioxide. This indicates that current policies are not sufficient to prevent carbon emissions in Beijing from increasing after their peak. If new policies are not considered and implemented, carbon emissions in the city will still increase in 2035, even after their peak in 2015. This increase is mainly determined by the transportation and industrial sectors. The contribution of carbon emissions increases by the transportation sector accounted for 46.20% (in 2035) and 35.44% (in 2050) of the total carbon emissions increase, respectively. More specifically, the carbon emissions increase from the urban transportation and inter-provincial passenger and freight transportation sectors were 28.27% and 18.00% of the total, respectively. Meanwhile, the manufacturing sector, which is a component of the industrial sector, reduced its carbon emissions by 17.22%. The carbon emission increase caused by the power and thermal power generation and supply sector was dominant and accounted for 52.60% of the total. Therefore, special attention should be given to the transportation and power and thermal power generation and supply sectors in the future.

3.1.4. Water demand

The results of the model showed that the total water demand in Beijing increased until its peak in 2028 (see Fig. 5). After that, it decreased until it increases again in 2041, fluctuating between 3.6 and 4.1 billion m^3. An analysis on the demand structure by sectors revealed that the proportion of the agricultural water consumption to the total consumption increased from 17.61% in 2015 to 24.93% in 2028, remaining at 22%–24% subsequently. The proportions of water consumption by the manufacturing, power generation and supply, and water production and supply sectors to the total consumption decreased continuously, reaching 1.1%, 1.98%, and 1.96%, respectively, in 2050. The proportion of water consumption from the tertiary sector to the total consumption firstly reduced, increasing afterwards. Its value was 16.44% in 2015 and dropped to 14.18% in 2018. After that, it increased continuously and reached 18.7% in 2050. The proportion of household water consumption fluctuated and its average over the prediction period was 21.23%. Furthermore, the proportion of environmental water consumption also fluctuated, becoming stable at about 30%.

In the scenario of winter sport development, together with the industry sector, in relation to the Winter Olympic Games, water consumption increased by less than 1%. In the model, the average annual increase was approximately 0.026 billion m^3. In the scenario with reduced family sizes, the water consumption in 2050 grew by 0.383 billion m^3, which is 10.74% of the total water demand.

The water demand related to energy consumption was 0.068 billion m^3 in 2050 and accounted for 2.45% of the total water demand, on average, over the prediction period. Specifically, water consumption by thermal power generation, hydro power generation, and other power generation methods accounted for 81.70%, 17.13% and 1.17% of the total energy consumption-related water demand, respectively.

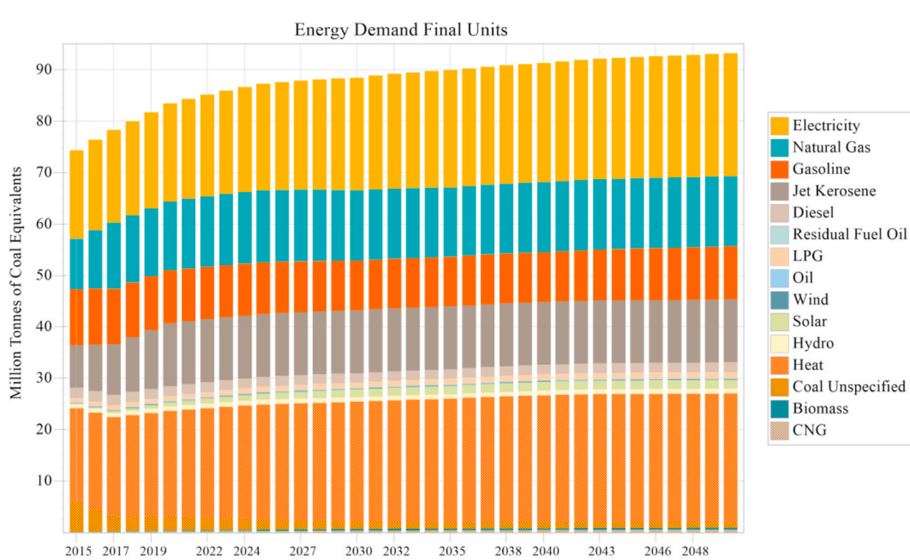

Fig. 4. Prediction of energy type structure for Beijing under the reference scenario.

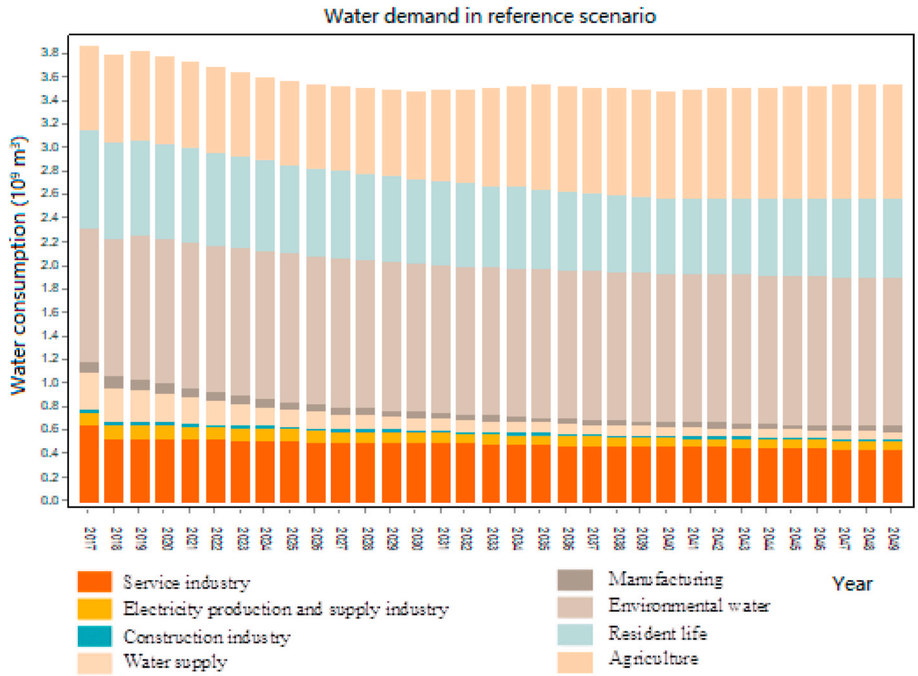

Fig. 5. Water demand of different sectors under the reference scenario.

3.1.5. Water supply

In the reference scenario, water demand can be satisfied. Nevertheless, in the BAU scenario, water resource shortages appeared in 2039 and continued to increase year after year, reaching 0.265 billion m^3 in 2050.

In the scenario, where supply is controlled, restricted groundwater exploitation led to a water supply shortage of almost 0.66 billion m^3. In the BAU scenario, if groundwater exploitation is further restricted, water shortages were reduced after 2016 and reached 0.448 billion m^3 in 2021. Subsequently, it increased and reached 0.972 billion m^3 in 2050. In the groundwater exploitation restriction scenario, based on the reference scenario, after a shortage in 2016, groundwater supply decreased year after year because the utilization rate of reclaimed water increased. Almost no shortage appeared after 2023. In the reclaimed water utilization scenarios, based on the baseline and reference scenarios, no water shortage emerged. Nevertheless, for the supply structure, the water sources are different, as shown in Table 1. When the total water demand is kept constant, the groundwater used in the reclaimed water utilization scenario was, on average, 10% less than that in the reference scenario. Thus, on average, 0.428 billion m^3 of groundwater was saved annually. In addition, the proportion of water transferred through the South-North Water Transfer Project to meet the total water demand reduced slightly. Lastly, in the scenario with an increased reclaimed water utilization rate, the proportion of reclaimed water to the total water demand reached up to about 40%, which was 15% higher than that in the reference scenario.

3.1.6. Energy-water nexus analysis by sectors

Fig. 6 showed a scatter plot between water and energy demands of different sectors. As shown in Fig. 6(a), the household sector and tertiary industry had relatively high water and energy demands at the same time. Specially, for the household sector, the energy demand was between 10 and 15 million tons of standard coal, while the water demand was between 0.8 and 1.0 billion m^3, being positively correlated. Similarly, in the tertiary industry, water and energy demand were positively correlated. The regression analyses proved that the regression slope for the tertiary industry (0.140, $R^2 = 0.78$) was smaller than that in the household sector (0.693, $R^2 = 0.8216$). That is, the associated water consumption per unit of energy consumption was lower. The agricultural sector had a relatively higher water demand, but its energy demand was not high compared to those of other sectors. There was no distinct positive correlation between the water and energy demands of this sector. In 2029, when the energy demand of the sector increased to 166.8 tons of standard coal, the water demand reached a maximum of 1.023 billion m^3, following which, the water demand reduced. For the water production and supply sector, even if the water demand increased, the energy demand did not change significantly. This is probably because the energy consumption in the South-North Water Transfer Project was not included in the energy consumption of this sector. Otherwise, a more distinguishable correlation may exist.

In Fig. 6 (b), a more detailed energy-water nexus relationship for the building sector, traditional and modern manufacturing sectors, and electric power sector are illustrated. The energy and water consumptions of the building sector exhibited a linear positive correlation ($R^2 =$

Table 1
Comparison of water supply sources between reference scenario and increased utilization of recycled water scenario.

Year	Reference scenario				Increased utilization of recycled water scenario			
	Surface water	Underground water	South-north transferred water	Recycled water	Surface water	Underground water	South-north transferred water	Recycled water
2020	7.33%	41.12%	26.52%	25.06%	7.33%	26.07%	26.52%	40.09%
2030	7.06%	29.58%	38.40%	24.96%	7.06%	19.28%	33.72%	39.91%
2040	7.32%	26.10%	41.15%	25.42%	7.32%	18.30%	33.70%	40.67%
2050	7.10%	26.90%	39.89%	26.11%	7.10%	17.62%	33.48%	41.78%
Average	7.23%	31.72%	35.64%	25.41%	7.23%	21.04%	31.49%	40.24%

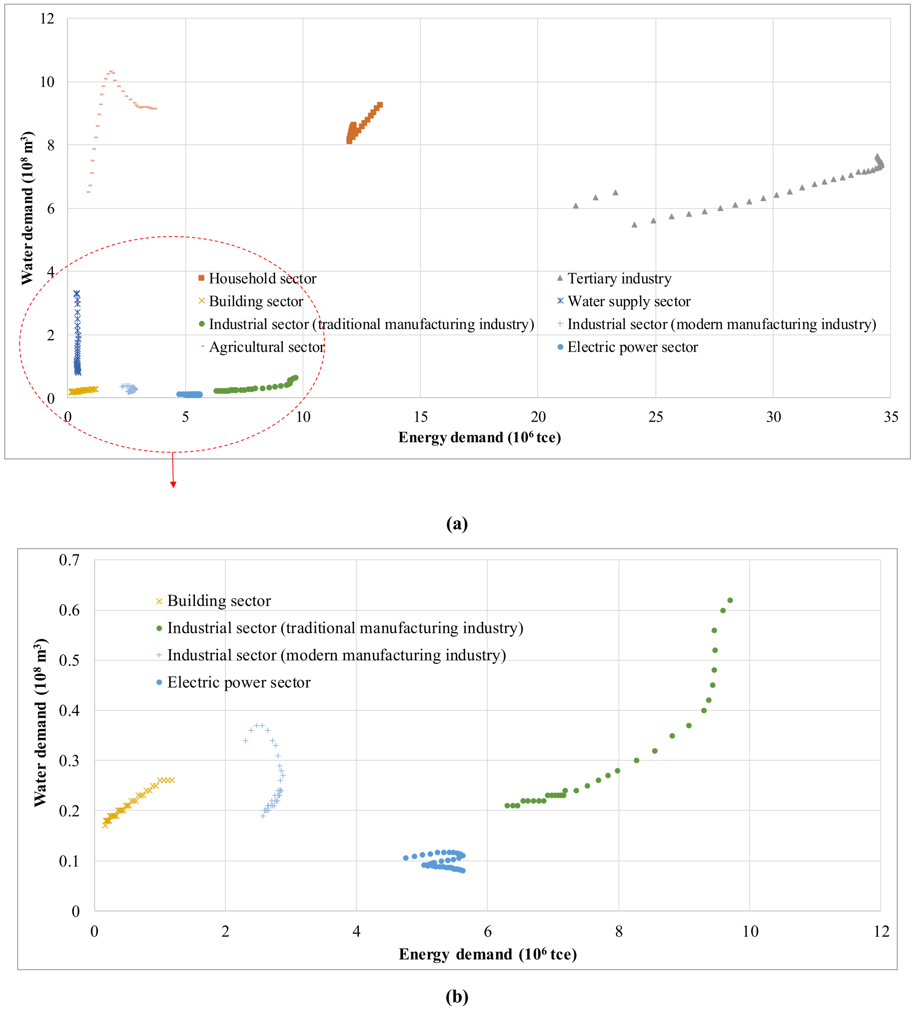

Fig. 6. Scatter plot between water and energy demands of different sectors.

0.9801). For the traditional manufacturing sector, as the energy demand increased, the water demand also grew. However, the growth became slow later on and the demand even dropped in some years. For the modern manufacturing sector, the water demand varied significantly, whereas the energy demand did not. The energy-water relationship between the electric power sector fluctuated. Sometimes, the demand for both energy and water increased. However, the energy demand increased, but the water demand declined, while, at other times, both decreased simultaneously. This depended on external electricity sources. The water consumption activity level of the electric power sector in the WEAP model was based on the power generation value from the transformation module in LEAP. Under the influence of external electricity, the power generation value reduced, while the total energy consumption increased. Meanwhile, in LEAP, the electric power sector was associated with the total energy demand. Therefore, the energy-water relationship of the sector fluctuated.

In summary, for the household sector, tertiary industry sector, building sector, and traditional manufacturing sectors, there existed relatively good correlations between their energy and water demands. In these sectors, energy and water demands varied synchronously. Hence, they are important energy-water nexus sectors.

3.2. Energy-saving effects for different scenarios

3.2.1. Energy-saving effects of core parameter variation scenarios

Among the core parameter variation scenarios (Type K), the industrial structure optimization scenario (K2) showed a relatively satisfactory energy-saving effect from 2015 to 2025. The energy consumption increased again after 2025. This is because, in 2025, new energy demands brought by continuous economic development equaled the energy demand reduction resulted from industrial structure optimization. This is related to the balance between the energy demand growth, caused by the tertiary industry sector and the energy demand decrease for the industrial sector. In 2025, industrial structure optimization saved 2.922 million tons of standard coal, while the energy demand of the tertiary industry sector increased by 1.454 million tons of standard coal. The difference between the two was 1.468 million tons of standard coal. The overall energy-saving effect is optimal at this moment. After 2025, the growth in energy saved by the industrial sector was smaller than that the energy demand of the tertiary industry sector, and the difference between them shrank continuously. Therefore, the overall energy-saving effect weakened. Hence, in the long term, if industrial structure optimization is employed to reduce the total energy demand, more intensive industrial restructuring should be carried out.

The energy-saving effect of the industrial structure optimization (I) scenario (K3) before 2020 was almost the same as that of the economic slowdown scenario (K1). In the long term, unlike industrial structure optimization (II), K3 scenario was capable of saving energy under continuous economic development. In the long and medium term, it can save energy to some extent. The best energy-saving effect was achieved by K1. By 2050, K1 could save up to 20.051% of energy. The population transfer scenario resulted from the construction of Xiong'an New Area (K5) only had a limited effect on the total energy demand reduction. By 2050, it could save 37.400 thousand tons of standard coal and 0.2% of

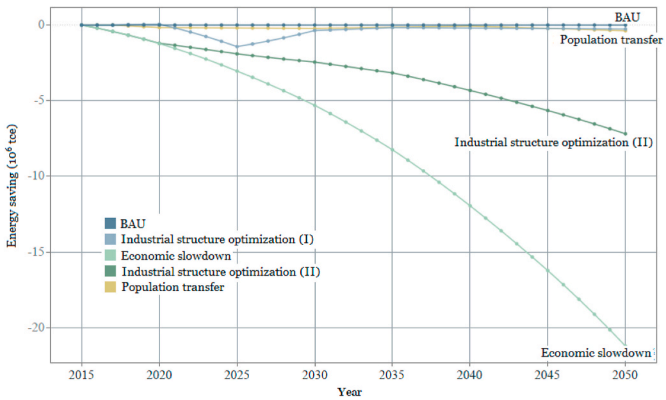

Fig. 7. Energy saving effects in key assumption change scenarios. Note that the amount of energy saved is negative, that is, the greater the absolute value, the better the energy saving effect.

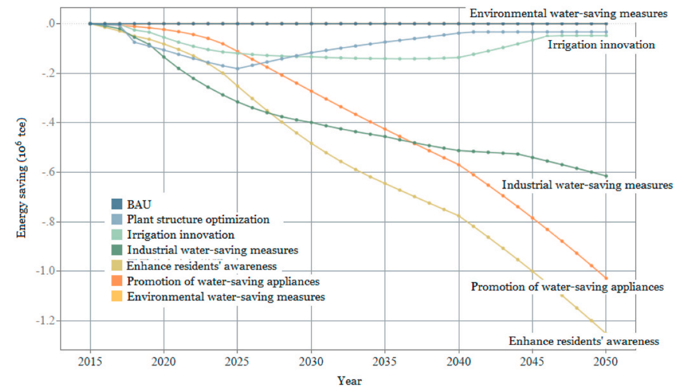

Fig. 9. Energy saving effects in water-saving goals scenarios. The amount of energy saved is negative showed in this figure, that is, the greater the absolute value, the better the energy saving effect.

energy (see Fig. 7).

3.2.2. Energy-saving effects of scenarios to achieve energy-saving goals

More energy was saved effectively in the scenarios, in which the goals of individual sectors were to save energy in comparison to the core parameter variation scenarios. The short-term saving effects didn't differ much from the medium- and long-term energy-saving effects. The amounts of energy saved in different scenarios all increased year after year. In particular, the terminal technology innovation in tertiary industrial sector (E7) had the greatest energy-saving potential (see Fig. 8).

By 2050, the energy saving ratio reached 29.43%. Hence, for current policies, the tertiary industrial sector is still a key energy-saving sector. Meanwhile, industrial technology innovation (E1) had the second highest energy-saving potential and it resulted in an energy saving ratio of 11.69% by 2050. The energy saving ratios of transportation measures were all below 5% by 2050. Transportation facility optimization (E4) can save more energy effectively than the electric vehicle promotion (E2), biomass fuels (E5), and public transportation development (E3). Nevertheless, the result may vary from a carbon emission perspective. By 2050, 2.56%, and 0.6% of energy was saved under the terminal technology innovation in household sector and the technology innovation in building sector, respectively.

3.2.3. Energy-saving effects of scenarios to achieve water-saving goals

In the scenarios used to achieve water-conservation goals, the overall amount of energy saved accounted for a maximum of 0.66% of the total energy demand. In different scenarios, the variations in the short-, medium- and long-term energy-saving effects differed. In terms of short-term effects, industrial water-saving measures (W3) led to the best energy-saving effect by 2020 (see Fig. 9). This was followed by plantation structure optimization (W2), enhancement of residents' awareness of water conservation (W6), irrigation technology innovation (W1), and promotion of water-saving appliances (W4).

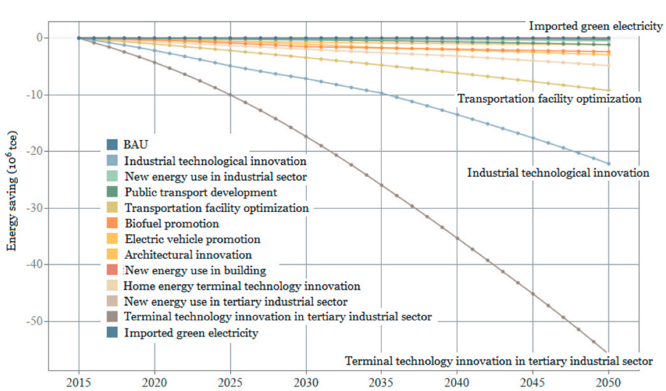

Fig. 8. Energy saving effects in energy-saving goals scenarios. Note that the amount of energy saved is negative showed in this figure, that is, the greater the absolute value, the better the energy saving effect.

By 2025, the energy-saving effect of the W6 scenario surpassed that of the W2 scenario, while the W4 and W1 scenarios saved almost the same amounts of energy. From 2025, the amounts of energy saved by two water-saving measures in the agricultural sector started to decrease, continuing until 2050. There was a turning point in this sector, because its structure optimization was basically completed in 2025. This sectorial water consumption reduced from 0.689 billion m^3 to 0.405 billion m^3 and the groundwater withdrawal dropped from 1.7 billion m^3 to 1.683 billion m^3.

The maximum amount of energy was saved at this time. As water consumption from the industrial and tertiary sectors continued to grow, the amount of groundwater exploited increased again, reaching, first, 1.7 billion m^3 and, then, becoming stable in 2041. As a result, the amount of energy saved became stable. Similarly, in the BAU scenario, the water supply couldn't satisfy the water demand in 2040. In the W1 scenario, water shortage appeared only after 2046. From 2040 to 2046, because water supply increases, the amount of energy saved reduced and became stable by 2046.

In the W4 and W6 scenarios, relatively good long-term energy-saving effects were evidenced. By 2050, each of them saved more than 1 million tons of standard coal. Energy was saved mainly by reducing energy consumption in water transportation and treatment. The variations in the amounts of energy saved were consistent with those in the amounts of water saved by the corresponding measures. The water-saving measures of the industrial sector were determined mainly by a decline of the industrial-reclaimed water treated together with the energy consumption. The energy saving curve for this scenario showed that the amount of saved energy reduced gradually, becoming more evident after 2044. This turning point exists because, in the model, the amounts of water withdrawn and produced were estimated by using water inflows as the activity levels, while the amount of water treated was estimated by adopting the water demands of demand points at the activity levels. Around 2044, in the scenario, where water-saving measures were employed in the industrial sector, water shortage appeared, while the water supply became constant.

For the period 2025–2044, the amounts of energy saved in water withdrawal and production decreased gradually, causing the total amount of energy saved to decrease slowly. After 2044, the variations in the total amount of energy saved were completely dependent on processes, such as sewage discharge and treatment, and reclaimed water treatment, becoming more distinct. In the model settings, environmental water consumption didn't include those in water withdrawal, production and transportation, and sewage treatment and household end-use energy and water consumption. Therefore, no energy could be saved for this component. The garden greening scenario (W5) almost coincided with the BAU scenario.

To summarize the results, for the agricultural sector, the W1 and W2 scenarios displayed relatively good short-term energy-saving effects. However, as water shortages appeared and further expanded, their medium- and long-term effects were insignificant. The water-saving measures taken in the industrial sector can effectively save energy in the short run. From 2018 to 2027, in all the scenarios, where water-saving measures were employed, optimal energy-saving effects were observed. In both short- and medium-to long-term, the energy-saving effects of the water-saving measures taken by the industrial sector varied only slightly. In the W4 and W6 scenarios, short-term energy-saving effects were not obvious. From 2025, the amounts of energy saved in these two scenarios increased considerably, surpassing surpassed those saved by the water-saving measures taken by the industrial sector in 2028 and 2038. Hence, the W4 and W6 scenarios exhibited relatively great long-term energy-saving potentials.

3.2.4. *Sensitivity analysis of energy-saving effects*

In the scenarios, where core parameters varied, model results were more sensitive to economic growth rate parameters. Different economic growth rates gave rise to different energy saving ratios, which were found to be 4.69%–19.96% (2050) with $\Omega_A = -5.8$ and $\Omega_C = 7.85$. In Fig. 10, in the industrial structure optimization scenario with parameter values reduced by 10% (industrial structure optimization C), the amount of energy saved shared the same variation patterns as those in the original scenario (Type B) and the scenario with parameter values increased by 10% (industrial structure optimization A) from 2015 to 2035. After 2035, the amount of energy saved in the industrial structure optimization C scenario increased. This indicates that, if more intensive industrial structure optimization is carried out, measures of this type can still have continuous reducing energy-saving effects in the long-term. For the scenario in which the populations transfer scenario, increasing or decreasing parameter values caused no significant differences.

Among the scenarios used to achieve energy-saving goals, the industrial technology innovation, public transportation development, transportation facility optimization, and household terminal technology innovation scenarios were relatively sensitive to variations in the parameters. In particular, the transportation facility optimization scenario was the most parameter-sensitive. In 2050, the energy saving ratios of the scenario were between -0.86% and 4.88% ($\Omega_A = -4.32$ and $\Omega_C = 12.11$). In 2050, the energy saving ratios of the scenarios with terminal technology innovation in the service and industrial sectors were -27.81%-30.88% ($\Omega_A = -0.55$ and $\Omega_C = 0.49$) and -10.26%-13.33% ($\Omega_A = -1.22$ and $\Omega_C = 1.41$), respectively. Meanwhile, the scenario with technology innovation in the construction sector was slightly parameter-sensitive. The final results fell between -0.88% and -0.99% ($\Omega_A = -0.68$ and $\Omega_C = 4.78$).

Among the scenarios used to achieve water-saving goals, only the plant structure optimization scenario was highly parameter-sensitive. The amount of energy saved peaked in 2030 in the plant structure optimization C scenario. However, in both the plantation structure optimization scenarios, the maximum energy savings were achieved in 2025. In the meantime, the irrigation technology innovation scenario was relatively sensitive to parameter variations from 2025 to 2045. In 2045, $\Omega_A = -3.23$ and $\Omega_C = 3.25$. In 2050, the result range reduced, with $\Omega_A = -0.61$ and $\Omega_C = 0.56$. Similarly, for the scenario where industrial water-saving measures were taken, there was relatively high variance from 2025 to 2045. By 2050, the variation became less significant, with $\Omega_A = -0.51$ and $\Omega_C = 0.49$. In the scenarios where residents' awareness of water conservation increased and water-saving appliances were promoted, the variation reduced gradually as we moved on from short-term results to long-term ones. For the scenario, in which residents' awareness of water conservation increased, the sensitivity indices were $\Omega_A = -0.37$ and $\Omega_C = 0.37$ in 2025, $\Omega_A = -0.26$ and $\Omega_C = 0.26$ in 2035, and $\Omega_A = -0.24$ and $\Omega_C = 0.24$ in 2050.

3.3. *Water-saving effects of different scenarios*

3.3.1. *Water-saving effects of core parameter variation scenarios*

Among the core parameter variation scenarios, the industrial structure optimization scenario (K2) slightly reduced the water demand in 2012–2017 (see Fig. 11). By 2020, there was a new water demand of more than 0.06 million m^3. After 2020, the increase in the water demand reduced gradually and eventually became stable at approximately 0.02 billion m^3. This is mainly because the water consumption by the tertiary sector increased. In 2020, in the K2 scenario, the water consumption by the tertiary sector increased by 64.1 million m^3 compared to that in the BAU scenario. Meanwhile, the water consumption by the water production and supply sector increased by 7.4 million m^3.

At the same time, the amount of water saved by the industrial sector was 6.3 million m^3, so the total water consumption grew by more than 60 million m^3. Subsequently, the increase in the water consumption by the tertiary sector remained at 63–64 million m^3 from 2020 to 2025 while the amount of water saved by the industrial sector increased to 16.1 million m^3 in 2025. Thus, the total water consumption reduced. From 2025 to 2030, the proportion of the water consumption by the tertiary sector compared to the total water consumption increased less rapidly and the water consumption by the sector dropped to 31.1 million m^3. As a result, the total water consumption declined.

In the economic growth slowdown scenario (K1), the total water

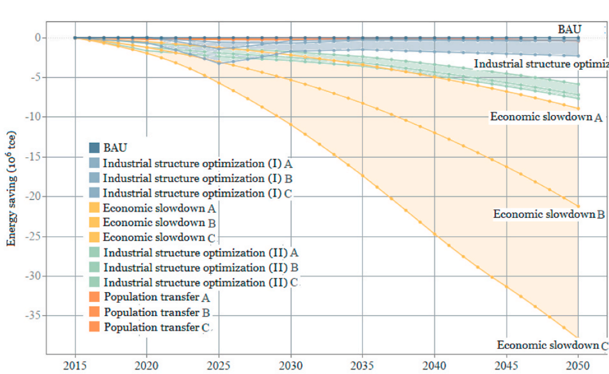

Fig. 10. Sensitivity analysis of energy saving effects in key assumption change scenarios. The amount of energy saved is negative showed in this figure, that is, the greater the absolute value, the better the energy saving effect.

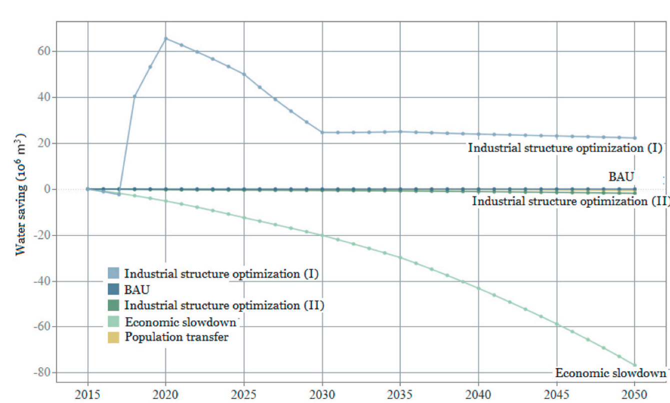

Fig. 11. Water saving effects in key assumption change scenarios. The amount of water saved is negative showed in this figure, that is, the greater the absolute value, the better the energy saving effect. The scenario above the x-axis in the graph represents an increase in water consumption.

demand only reduced by 1.64% by 2050. A gap between this value and the energy ratio of 20.05% was observed for this scenario. This is because, in the LEAP model, all activity level variables are associated with economic variables, except those of energy consumption by the household and transportation sectors. Meanwhile, in the WEAP model, the activity level of the water-consuming agricultural sector was defined as the total area of grain fields, whereas those of the service and household sectors were defined by the population. Thus, the economic growth didn't significantly affect the WEAP results. No considerable water-saving effects were observed in the industrial internal restructuring (K3) scenario and the scenario in which Xiong'an New Area accommodates population relocation from Beijing (K5).

3.3.2. Water-saving effects of scenarios to achieve water-saving goals

In the scenarios, used to achieve water-saving goals, different variation patterns were noted for water-saving effects of different measures in the short-, medium-, and long-term. In Fig. 12, the plant structure optimization scenario (W2) showed an optimal water-saving effect before 2028.

After that, the amount of water saved became stable at 0.320 billion m^3. In the scenarios with irrigation technology innovation (W1) and industrial water-saving measures (W3), almost the same water-saving effects were noted before 2035. After 2035, the amount of water saved by irrigation innovation varied slightly. Meanwhile, while the industrial water-saving measures continued to decrease, the water saving ratio of the W3 scenario reached 13.21% of the total water demand by 2050. In terms of the total water demand, the scenarios, where residents' awareness (W6) and water-saving appliances promotion (W4) were enhanced, relatively satisfactory water-saving effects were obtained. The variations in the amounts of water saved in these scenarios with time were basically identical. They had insignificant short-term effects, but they were effective medium- and long-term. The water-saving effect of the scenario, where environmental water-saving measures (W5) were taken, did not change considerably with time. Over the prediction period, the amount of water saved in this scenario declined rapidly. By 2050, the water saving ratio was 4.24%.

3.3.3. Water-saving effects of scenarios to achieve energy-saving goals

Among the scenarios used to achieve energy-saving goals, the scenario where external green electricity was imported (E12) had the optimal water-saving effect. Its water saving ratio reached 6.85% by 2050 (see Fig. 13). The scenario with terminal technology innovation in tertiary sector (E7) also gave a relatively satisfactory water-saving effect and yielded a water saving ratio of 3.23% in 2050. The variations in the water-saving effect with time suggest that the amount of water saved by importing green electricity rapidly increased from 2015 to 2020. Its reduction rate slowed down from 2020 to 2050. A turning point

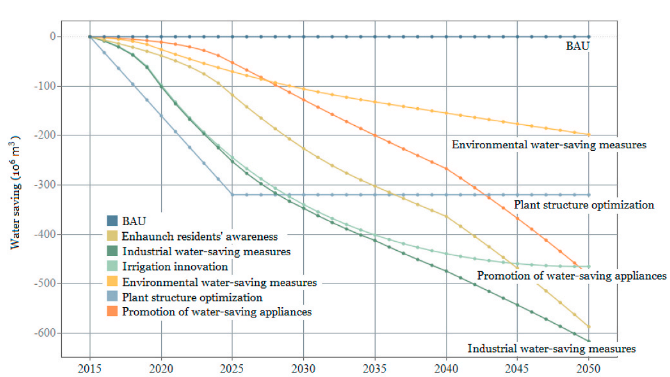

Fig. 12. Water saving effects in water-saving goals scenarios. The amount of water saved is negative showed in this figure, that is, the greater the absolute value, the better the energy saving effect.

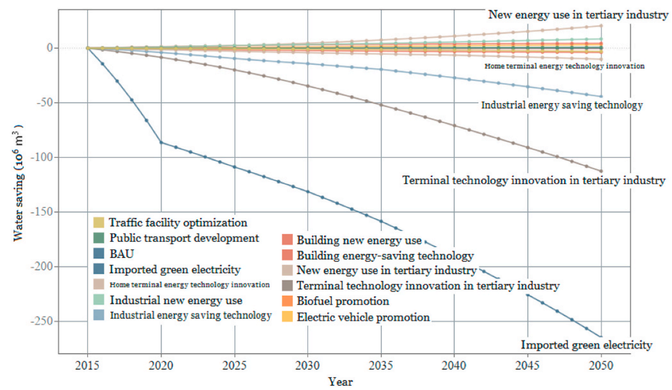

Fig. 13. Water saving effects in energy-saving goals scenarios. The amount of water saved is negative showed in this figure, that is, the greater the absolute value, the better the energy saving effect. The scenario above the x-axis in the graph represents an increase in water consumption.

appeared in 2020, because the proportion of thermal power to the total power generation reduced from around 30%–10% from 2015 to 2020. After that, a yearly reduction by 0.3% was evidenced, until thermal power was completely replaced.

The new water demands in the E9, E10, and E11 scenarios accounted for 0.18%, 0.10% and 0.07% of the total demand, respectively. As previously mentioned, while the promotion of electric vehicles reduced the total energy demand, it caused the proportion of electricity compared to the total power consumption to increase. As a result, the total electricity demand experienced a net increase. Increased power generation led to a greater water demands.

3.3.4. Sensitivity analysis of water-saving effects

The industrial structure optimization ($\Omega_A = -11.46$ and $\Omega_C = 9.75$ in 2050) and economic growth slowdown ($\Omega_A = -5.80$ and $\Omega_C = 7.85$) scenarios were relatively parameter-sensitive. In particular, in the industrial structure optimization A scenario, a noticeable water-saving effect was found from 2030 onward. This revealed that, in the scenarios used to achieve water-saving goals, attention should be placed on the intensity of industrial structure optimization. Meanwhile, in scenarios used to achieve energy-saving goals, more intensive industrial structure optimization leads to a more long-lasting increase in the amount of energy saved. When the aim is to reach both energy- and water-saving goals simultaneously, policies should be scientifically designed to realize joint energy and water-saving effects. Although industrial internal restructuring didn't result in a considerable water saving ratio, it was relatively parameter-sensitive ($\Omega_A = 2.35$ and $\Omega_C = 5.06$).

All scenarios, aiming to achieve energy-saving goals, were highly parameter-sensitive, except than the scenarios with terminal technology innovation in the tertiary sector ($\Omega_A = -0.57$ and $\Omega_C = 0.51$ in 2050) and the introduction of new energy sources in the construction sector ($\Omega_A = -0.58$ and $\Omega_C = 0.40$ in 2050). Specifically, the public transportation development scenario was the most sensitive to parameter variations ($\Omega_A = -4.38$ and $\Omega_C = 6.57$ in 2050). The sensitivity indices of the external green electricity importation scenario were $\Omega_A = -0.92$ and $\Omega_C = 0.92$ in 2020. Thus, this scenario didn't appear to be highly parameter-sensitive. The gap between the electricity demand and supply first increased and, then, decreased, when different amounts of external green electricity were imported. This is because the proportions of imported external green electricity compared to the total power generation at the early stage in different scenarios determined the amount of power generated through different methods, and thereby the total water consumption in power generation. As the demand for electricity increased while the electricity supply capability of the city gradually approached its upper limit, the demand eventually became consistent with the

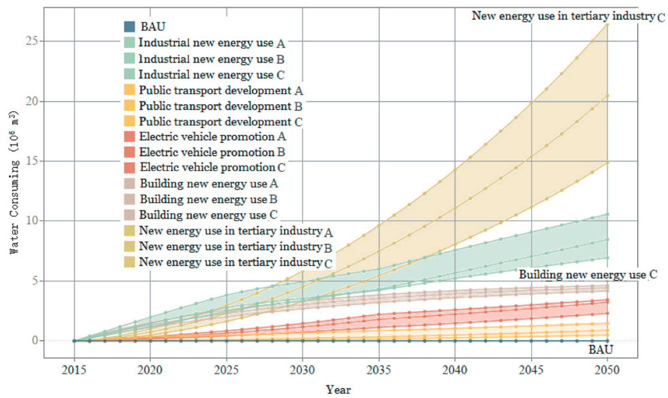

Fig. 14. Sensitivity analysis of water consuming effects in energy-saving goals scenarios. The amount of water saved is negative showed in this figure, that is, the greater the absolute value, the better the energy saving effect. The scenario above the x-axis in the graph represents an increase in water consumption.

supply.

As shown in Fig. 14, among the scenarios used to achieve water-saving goals, the plantation structure optimization scenario ($\Omega_A = -1.4$ and $\Omega_C = 1.4$ in 2050) and the scenario in which environmental water-saving measures were adopted ($\Omega_A = -7.5$ and $\Omega_C = 8.1$ in 2050) were relatively sensitive. For the remaining scenarios, the sensitivity indices Ω_A were greater than -1 while the values of Ω_C were smaller than 1. For the scenarios where residents' awareness of water conservation increased and water-saving appliances were promoted, the absolute values of the sensitivity indices were less than 0.3 in 2050.

3.4. Energy- and water-saving nexus effects of different scenarios

Some measures were designed to save energy or water, but side effects may result during their implementation. Energy-saving measures may reduce water demands and achieve joint energy- and water-saving effects. Nevertheless, they can also increase water demands. On the whole, the water saving ratios brought about by energy-saving measures were greater than the energy saving ratios caused by water-saving measures. This is because the proportion of water needed during energy consumption compared to the total demand is higher than that of energy needed during water consumption.

Energy- or water-saving measures, taken by different sectors, have different joint effects. These depend on the energy and water consumption by the sector. For the tertiary sector, energy and water consumption was high, so terminal technology innovation of the sector can save energy and water effectively (by 29.43% and 2.41%, respectively). Being one of the dominant energy-consuming sectors, the industrial sector can save a lot of water, when energy-saving measures are considered. For instance, industrial technology innovation can save energy by 11.69% and water by 0.95%. For the agricultural sector, energy- or water-saving measures designed for the sector lead to insignificant joint effects. While the agricultural sector is a major water-consuming sector, water-saving measures taken by this sector only has slight energy-saving effects. On one hand, industrial water and energy consumption are high, initially, while the agricultural sector consumes relatively less energy even without these measures. On the other hand, the proportion of water used during energy consumption compared to the total water consumption is greater than that of energy used during water consumption compared to the total energy consumption.

Even for measures of the same sector, their joint effects vary according to the variables controlled. In scenarios with industrial technology innovation, terminal technology innovation of the tertiary sector and transportation facility optimization, energy consumptions are controlled and certain joint energy- and water-saving effects are noted. Meanwhile, energy structure optimization (including the introduction of new energy sources in the industrial, construction, and tertiary sectors) and industrial structure optimization can effectively reduce energy consumption and carbon emissions, but they increase water demands.

Furthermore, it was found that different parameter adjustments of the same measure resulted in two different distributions of scatter points. One type represents independent energy- or water-saving effect variations. Examples are water-saving measures taken by the industrial sector and irrigation technology innovation. Their resulting scatter points are distributed parallel to the x- or y-axis. The other type of distribution represents joint energy- and water-saving effects. Examples are economic growth slowdown, industrial technology innovation, and terminal technology innovation of the tertiary sector. Their water-saving effects change with the energy-saving effects.

3.5. Joint effects of energy- and water-saving measures in Beijing during the Thirteenth Five-Year Plan period

According to the modeling results, the energy-saving measures in Beijing during the Thirteenth Five-Year Plan Period saved up to 0.276 billion m^3 of water. In particular, public transportation development, promotion of electric vehicles, and the introduction of new energy sources in the industrial, construction, and tertiary sectors increased the water demand by 0.01 billion m^3, whereas other measures saved up to 0.286 billion m^3 of water. A net amount of 0.276 billion m^3 of water was saved. This amount is half of the average annual runoff of the North Canal River or equivalent to the water storage capacity of 140 Kunming Lakes (in the Summer Palace, Beijing). Meanwhile, the water-saving measures saved up to 1.003 million tons of standard coal. This was equivalent to 8.165 billion kWh of electricity and 7.65% of the total electricity consumption by Beijing in 2017.

3.6. Evaluation of the comprehensive effects of energy-saving measures

Amounts of energy and water saved or emissions reduced were the only criteria to evaluate various measures. In the application study of comprehensive assessments of climate change by Mi [45]; for regional energy-saving measures, the effectiveness of a measure under climate change can be reflected by efficiency, emission variation, emission level, energy structure variation, and difference between the expected and real performances. Based on the climate change mitigation index (CCMI) proposed by Mi [45]; effects of different measures are evaluated. The weight of an indicator in the CCMI calculation is used to represent the contribution of the emission reduction measure corresponding to the indicator in a comprehensive evaluation. The selection priorities of different measures are then illustrated.

In this study, indicators employed are: CO_2 emissions during power generation and heating (10%), industrial CO_2 emissions (8%), CO_2 emissions from the construction sector (3%), CO_2 emissions from the transportation sector (3%), CO_2 emissions from the tertiary sector (excluding the transportation sector) (3%), household CO_2 emissions (3%), the energy consumption value (2%), the energy consumption variation (8%), the proportion of non-fossil-fuel-sourced energy to total energy consumption (2%), and the variation in the proportion of non-fossil-fuel-sourced energy (8%). According to the weight of each indicator, contribution of each emission reduction measure to the net reduction was estimated. The results are as summarized in Table 2.

It was discovered that, among existing measures, importation of external green electricity, introduction of new energy sources in the industrial sector, and industrial technology innovation play highly important roles in the comprehensive evaluation of measures. Therefore, they are critical in the low-carbon development of Beijing.

Table 2
Assessment weight of comprehensive emission reduction effect of energy saving target measures.

Rank	Scenario No.	Measures	Weight
1	E12	Imported green electricity	20%
2	E9	Industrial new energy use	18%
3	E1	Industrial structure innovation II	16%
4	E5	Biomass fuel promotion	13%
4	E6	Building energy-saving technology	13%
4	E7	Terminal technology innovation in tertiary industry	13%
4	E8	Home terminal energy technology innovation	13%
4	E10	Building new energy use	13%
4	E11	Use of new energy in tertiary industry	13%
4	E2	Electric vehicle promotion	13%
11	E4	Traffic facility optimization	11%
12	K3	Industrial structure innovation I	10%
13	E3	Public transport development	5%

4. Discussion

4.1. Comparison of this study with previous applications of LEAP-WEAP model

Our model considered the actual current situation and the unique characteristics of Beijing and provided a fine division of sectors. It can realistically reflect the energy and water consumption, carbon emissions, and the energy-water-carbon nexus relationships in the city in the future. However, Beijing is a mega-city, with extremely insufficient water resources and highly reliant on water imports. A relatively great energy consumption is observed, when water is transferred over long distances and groundwater is exploited. In the model, the water production and supply sectors were divided into four components. They included water extraction, water supply, water purification and waste water treatment. In particular, water supply as further divided into three processes: surface water, and groundwater extraction, and transferred water by the South-North Water Transfer Project. Considering that Beijing has more than 20 million permanent residents. Energy-water nexus relationship of the household sector are relevant. The proposed model also calculated household water consumption during activities, such as drinking water, taking showers, and taking laundry. A comparison between the results of this study and previous studies is summarized in Table 3.

Table 3
Comparison of the LEAP-WEPA model applied in this study and previously applied LEAP-WEAP models.

Model detail	LEAP-WEAP Beijing (This study)	LEAP-WEAP JingJinJi [42]	LEAP-WEAP Xiamen [39]
Boundary	Beijing	Power sector of Jing-Jin-Ji region	Xiamen
LEAP sector division	Agricultural sector, manufacturing sector (traditional and modern manufacturing sectors), electric power sector, water supply sector, transportation sector, Tertiary sector, household sector	Primary sector, secondary sector, tertiary sector, household sector	Business sector, manufacturing sector, transportation sector, agricultural sector, household sector
WEAP sector division	Agricultural sector, manufacturing sector (traditional and modern manufacturing sectors), electric power sector, water supply sector, transportation sector, Tertiary sector, household sector, and eco-environmental water use	Primary sector, secondary sector, tertiary sector, household sector	Business sector, manufacturing sector, transportation sector, agricultural sector, household sector
LEAP data link to WEAP	Different electricity generation patterns	Different electricity generation patterns	Different electricity generation patterns
WEAP data link to LEAP	(1) supply side: water-intake (surface water, groundwater, south-to-north water diversion); Water system; Carrying capacity; Sewage discharge water treatment capacity; Renewable water (2) demand side: water consumption accompanied by energy demand in daily life, such as bathing, washing and cooking	Hydroelectricity generation	(1) supply side: water intake, transportation and wastewater treatment volume (2) demand side: water consumption accompanied by energy demand in daily life, such as bathing, laundry and cooking; Water consumption associated with energy demand, such as bathing and washing, in the commercial sector; Commercial manufacturing processes use cooling and cleaning water

4.2. Implementation difficulties of measures

4.2.1. Difficulties in implementing energy-saving measures

Three types of technologies are involved, when measures are taken by different sectors. In ascending order of implementation difficulty, they are: technologies to adjust the energy structure, those to enhance efficiency, and those to adjust internal structures of sectors. Their technical difficulty weights were set to 17%, 33%, and 50%, respectively, according to the ratio of 1:2:3 [45,46].

The transformation difficulty weight for each energy-saving measure is determined by the emission reduction cost of each technology. Specifically, the emission reduction cost for the introduction of new energy sources in the electricity sector was 1163 CNY/ton of CO_2 [47], while the cost to reduce energy consumption by the electricity sector was 3700 CNY/ton of CO_2 [48]. The emission reduction cost in upgrading the structure of the manufacturing sector was 7789 CNY/ton of CO_2 [49], whereas the cost to reduce energy consumption by the manufacturing sector was 1880 CNY/ton of CO_2 [50]. The emissions reduction cost of the construction sector was 691 CNY/ton of CO_2 [51]. The emissions reduction cost in public transportation development was 287 CNY/ton of CO_2 [52], while that of promoting alternative fuel vehicles and biofuels was 7500 CNY/ton of CO_2 [53]. The emission reduction cost in lowering energy consumption by the transportation sector was 442 CNY/ton of CO_2, while that by the tertiary sector was 600 CNY/ton of CO_2 [3]. The carbon saving cost of the external electricity was calculated by multiplying the household electricity price and the amount of carbon saved per kWh. The household electricity price in Beijing was 0.5383 CNY/kWh and the carbon footprint of 1 kWh of electricity was estimated to be 1.0416 kg. Hence, the marginal emission reduction cost of the external electricity in Beijing was 469 CNY. The emission cost of each measure was converted into its transformation difficulty weight (in percentage). After that, the implementation difficulty of each measure was obtained by multiplying its transformation difficulty weight and its technical difficulty weight. The results are summarized in Table 4.

It was found that the structure implementation for the manufacturing sector is the most difficult. In addition, the promotion of

Table 4
Transformation, technical and implementation difficulty of each emission reduction measure.

No.	Scenario No.	Measure	Transformation difficulty	Technical difficulty	Implementation difficulty	Reference
1	K3	Industrial structure innovation I	32.50%	50%	16.25%	Electricity and manufacturing sector: [47–50,54];
2	E5	Biomass fuel promotion	31.30%	17%	5.32%	Building sector: [51];
3	E2	Electric vehicle promotion	31.30%	17%	5.32%	Transportation sector: [52,53];
4	E1	Industrial structure innovation II	15.40%	33%	5.08%	Tertiary industry [55]:
5	E6	Building energy-saving technology	2.90%	33%	0.96%	
6	E9	Industrial new energy use	4.90%	17%	0.83%	
7	E7	Terminal technology innovation in tertiary industry	2.50%	33%	0.83%	
8	E8	Home terminal energy technology innovation	2.50%	33%	0.83%	
9	E4	Traffic facility optimization	1.80%	33%	0.59%	
10	E10	Building new energy use	2.90%	17%	0.49%	
11	E11	Use of new energy in tertiary industry	2.50%	17%	0.43%	
12	E12	Imported green electricity	1.95%	17%	0.33%	
13	E3	Public transport development	1.20%	17%	0.20%	

biofuels and alternative fuel vehicles, as well as the reduction of energy consumption by the industrial sector per added unit value were technically difficult [46] Conversely, external green electricity importation and public transportation development could be easily realized.

4.2.2. Implementation difficulties in relation to water-saving measures

Similarly, sectorial water-saving measures can be classified into three types: measures to adjust activity levels, those to increase water consumption, and those to adjust internal structures of sectors. The measures to adjust activity levels and those to increase water consumption are equally difficult to implement, whereas those to adjust internal structures of sectors are harder to realize. Their technical difficulty weights are 25%, 25%, 50%, respectively [45]. The transformation difficulty weight of each water-saving measure was determined using the water saving cost of the technology. For example, the water saving cost of employing sprinkler irrigation systems in agricultural irrigation optimization is 6.1 CNY/m^3 [56]. This value was applied as the reference for water-saving measures in garden greening. In 2016, the promotion of water-saving appliances started in Beijing. The Beijing Water Authority provided a subsidy of 200 CNY to each household. Assuming that each household saved 6 m^3 annually and the service life of the water-saving appliance is five years, the marginal water saving cost was 6.7 CNY/m^3. According to the 2017 Beijing Hydrological Statistical Yearbook, in 2016 the water-saving technological transformation measures saved 3.49 million m^3 of water, investing 0.383 billion CNY in the transformation. The marginal cost of water-saving technological transformation was calculated and the obtained value was 123 CNY/m^3. This value was adopted as reference for the water saving cost of industrial water-saving measures. For measures used to enhance the awareness of water conservation, the water saving cost was estimated, based on the labor cost paid to the personnel engaged in related industries. According to the 2017 Beijing Hydrological Statistical Yearbook, in 2016 there were two educational departments under the Beijing Water Authority and a total of 224 employees. It was assumed that the investment per employee is 10,000 CNY. The 2017 Beijing Hydrological Statistical Yearbook reported that, in 2016, 0.031 million m^3 of water were saved through comprehensive management measures in Beijing. Assuming that the residents' enhanced awareness in relation to water contributed to 50% of the saved water, the marginal water saving cost of this measure was 1.4 CNY/m^3. As no relevant data were found for industrial plants and structure optimization, no discussions are presented here.

The water saving cost of each measure was converted into its transformation difficulty weight (in percentage). Subsequently, the implementation difficulty of a measure was defined as the product of its transformation difficulty weight and its technical difficulty weight. The results are given in Table 5.

Among the six scenarios, the scenario in which industrial water-saving measures were taken is the most difficult to implement. This is followed by the scenarios in which water-saving appliances are promoted, when water-saving measures are employed in garden greening, and when irrigation optimization is performed. Residents' enhanced awareness of water conservation is the easiest to realize. Thus, priority can be given to this measure.

4.3. Possible future challenges

4.3.1. Sub-replacement fertility

In the future, due to population ageing and the possibility of increasing numbers of married couples, that choose not to have children, Beijing may experience a severe sub-replacement fertility [58]. Therefore, family size may shrink. In the model, the energy and water consumption based on family size reduction scenario was examined. The modeling results suggested that family size reduction increased the energy demand by 1.60 million tons of standard coal in 2050, compared to the reference scenario. This accounts for 1.72% of the total energy demand. Meanwhile, more significant pressures on water resources were also identified. In 2050, family size reduction increased the water

Table 5
The transformation, technical and implementation difficulty of each water saving measure.

No.	Scenario No.	Measure	Transformation difficulty	Technical difficulty	Implementation difficulty	Reference
1	W3	Industrial water-saving measures	50%	47.28%	23.64%	Agricultural sector, landscaping sector: [56];
2	W4	Water-saving appliances promotion	50%	2.56%	1.28%	Water-saving measures [57]: Household sector [57]:
3	W6	Water saving in landscaping	50%	2.34%	1.17%	
4	W1	Irrigation optimization	50%	2.34%	1.17%	
5	W5	Enhance residents' awareness	25%	0.54%	0.13%	
6	K3	Industrial structure optimization	25%	–	–	
7	W2	Plant structure optimization	25%	–	–	

demand by 0.383 billion m^3, which was 10.74% of the total water demand.

4.3.2. Organization of large-scale events and construction of infrastructure

In 2019, a new airport was opened, while the World Horticultural Exposition was hold in Tongzhou district (Beijing). In 2022, the Winter Olympic Games will be jointly held in Beijing and Zhangjiakou. Hence, in the future, the organization of various major events and construction of infrastructures will impose new pressures on energy and water resources. The modeling results revealed that projects, such as the construction of the new airport and Universal Studios, and the organization of the Winter Olympic Games and the World Horticultural Exposition increased the total energy demand by 5%–6% each year. In the scenario with winter sports development, the development of the ice industry boosted by the Winter Olympic Games caused a yearly increase of water consumption lower than 1%. The simulated average annual growth in water consumption was approximately 0.026 billion m^3. Throughout these projects, water consumption efficiency should be enhanced as much as possible.

5. Conclusion

Based on LEAP and WEAP, this paper established a coupled model for water and energy supply and use for cities. Due to its size, environmental and social contains, and future expansion, Beijing was used as case study. During this study, 26 scenarios were designed to explore the energy saving/water saving of different policies. The applied model implemented the accounting of energy and water nexus and its effects. A sensitivity analysis of the results was also conducted. The results showed that, if energy- and water-saving effects of a measure are considered separately, terminal technology innovation of the tertiary sector had the optimal energy-saving effect, while industrial and household water-saving measures had relatively good water-saving effects. In terms of joint energy- and water-saving effects, the measures taken by the service and industrial sectors were more effective. Although the elimination of outdated industry at the provincial level and the promotion of new energy sources can effectively reduce emissions, they may increase water demands. This study allowed to implement an integrated method for accounting and designing energy- and water-saving goals, that could well support the definition of appropriate policies for resources conservation.

Considering the comprehensive effects and implementation difficulties for the measures, defined by existing policies and plans in Beijing, industrial energy-saving measures led to greater contributions to the net saving effect. However, industrial energy- and water-saving measures are hard to implement. Relatively speaking, public transportation development is the easiest one to implement, while enhancing residents' awareness of water conservation is the simplest water-saving measure. In the future, more attention should be placed on measures in these two areas. During policy evaluation, importation of external electricity has a relatively prominent performance. It is advantageous in terms of its comprehensive effect and implementation difficulty. More external electricity can be imported in the future, after the safety and stability of power supply system is guaranteed.

Controlling the population size while suppressing sub-replacement fertility can also help conserve energy and water. The energy and water demand during the organization of major events, such as the Winter Olympic Games, and construction of infrastructure, like the new airport, should also be monitored.

Author contribution

GY Liu were responsible for overall project supervision, conceptualization, project management, and final draft writing, review and editing; JM Hu contributed to methodology development, conducted validation, and contributed to the writing of early drafts; CC Chen, LY Xu, N Wang, FX Meng, BF Giannetti, F Agostinho and CMVB Almeida contributed to the data curation and revision checking; M Casazza contributed to the writing and polishing of final drafts.

Declaration of competing interest

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

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Appendix A. Supplementary data

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