Scenario analysis of low-carbon development of energy industry with restriction of water resource in Xinjiang

Aijun Li, Yuhao Liu, Guoshi Chen and Mingming Hu

ABSTRACT

This study empirically analyzes the prospects of the energy industry with the limited water resource in Xinjiang by extending an energy economic model. First, the past trends of water use in Xinjiang are analyzed. Energy utilization and industrial added value by sector are also investigated. Then, several important parameters such as economic growth rate, water saving rate, and energy saving rate are set exogenously. Especially, coal exploitation and utilization are selected as a typical case for studying energy development plan and technology choice. By keeping within the water requirement 'red line' and water security strategy, the acceptable speed and the future scale of the energy industry in Xinjiang are selected among several scenarios. Moreover, the interactions of economic growth, energy development, energy consumption, water requirement, and carbon dioxide emissions in Xinjiang are also analyzed. Finally, the technology choice of coal exploitation and utilization in Xinjiang with restriction of limited water resource is also suggested.

Key words | carbon dioxide emissions, energy development, input–output model, water resource

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INTRODUCTION

As China is implementing the strategy of developing the 'land silk road economic belt' and under-developed western provinces, Xinjiang Uygur Autonomous Region (i.e. Xinjiang) has been concerned more and more because of its geographic position adjacent to central Asia and Russia, with its vast lands and rich products in Western China. The resource reserves of coal, oil, and gas in Xinjiang are forecasted to rank top in China. In terms of large-scale renewable energy utilization such as wind and solar energy, Xinjiang is also regarded as one of the regions with most potential in China. Recently, Xinjiang has approved the construction of a large-scale multi-purpose national energy base during the 13th five-year-plan period (2016–2020) (NDRC Net 2017).

However, there are several challenges that Xinjiang must face during the construction of the strategic energy base. The first is the low-density population, relatively undeveloped economy, and limited consumer market within Xinjiang. Second, the distance from the central consumer market is so great that energy transport is very expensive. Other problems related to local resources and environment in Xinjiang are scarce water resources and a fragile ecological environment. In fact, the shortage of water resources has been especially serious in Xinjiang. Although the land area of Xinjiang accounts for one-sixth of China, the total water resources only occupy 2.9% of the country (People Net 2008). The per capita water resources in Xinjiang are 4,000 m^3, which is twice the average value of the country. However, the average amount of water produced per unit of area is only 53,000 m^3 per square kilometer, ranking the third lowest in China (XJSLT Net 2017a). The amount of water per unit of area in Xinjiang only accounts for 21% of the national average level (People Net 2008). In 2015, the total water requirement

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in Xinjiang was about 57.718 billion m^3 (XJSLT Net 2017b). However, the controlling red line of total water requirement in 2015 in Xinjiang was 51.560 billion m^3 (Meng 2015). Thus, the amount of water shortage in 2015 Xinjiang was 6.168 billion m^3.

Water scarcity in Xinjiang has combined with many regional special issues. For example, its ecological environment is extremely fragile, the agricultural irrigation mode is rather extensive, and the climate condition is very special. Moreover, the geographical distribution of water resource in Xinjiang is not balanced. Undoubtedly, the shortage of water resource also affects the choice of technology for the energy industry in Xinjiang. In such a situation, the planning of the construction of the national energy base in Xinjiang should fully consider the restriction of limited water resources.

For the estimation of a reasonable scale of coal exploitation and utilization, a hybrid energy model is extended in this study by applying the 2007 Xinjiang input–output table, which has 42 sectors (XBS 2009). Exogenous parameters in this model are set for the description of water shortage, energy saving, carbon mitigation, and technological progress in Xinjiang. The total water requirement red line in Xinjiang and the national CO_2 reduction planning target are set as restriction conditions. Technological schemes for coal exploitation and utilization in selected water saving and low-carbon development scenarios are assessed and chosen, and energy consumption and the related carbon dioxide emissions in Xinjiang by 2030 are predicted. Then, the development scale for coal exploitation and utilization in Xinjiang with the restriction of limited water resources is forecast. Finally, a policy suggestion for low-carbon development of coal exploitation and utilization in Xinjiang is given.

MODEL

As mentioned above, Xinjiang can provide a guarantee for sufficient energy supply in the long term in China. However, the shortage of water resources has become a large obstacle for low-carbon development of the energy industry in Xinjiang. The planning of energy development in Xinjiang should consider many factors such as energy exploitation conditions, energy technology choice, local water resource constraints, and economic development mode. The most sensitive factors that affect the accuracy of results in this study are the setting of the value of the gross domestic product (GDP) growth rate and water saving rate.

Since an input–output model can clearly reflect the interaction relationship of multiple-sectors, it is applied in this study by combining it with an energy engineering sub-model and water requirement sub-model in terms of hybrid modeling. Especially, this hybrid energy–economic model is revised and developed from a hybrid input–output model that was built to study the total quantity target of Hubei Province carbon emissions trading system (Li *et al.* 2014). To analyze the low-carbon developments of China, hybrid energy–economic modeling methods have been applied in our previous studies (Li *et al.* 2016, 2017a, 2017b).

Parameters concerning socio-economics, including population, GDP growth rate, and urbanization rate are exogenously given. The urbanization rate is decomposed to industrial structure change by three main industries. In addition, parameter setting especially considers energy development planning and water resource restrictions. The RAS method is used here to estimate the direct requirement coefficient in a future target year. It is an adjustment technique to bi-proportionally (i.e. matrix R and S) modify the elements of a certain non-negative matrix (i.e. matrix A). Thus, by applying an iterative algorithm, the substitution matrix and manufacture matrix are used to modify the direct requirement matrix for the base year.

Three engineering sub-models are linked with the input–output model, and are used for the estimation of energy consumption, carbon dioxide emissions, and water requirement by sector. Then, the growth speed and development scale of the energy industry can be predicted under several given scenarios regarding economic growth modes and energy developments.

Regarding the energy consumption sub-model, a transformation matrix that transforms physical units to monetary units is constructed in the energy consumption sub-model, which is composed of energy conversion factors. Such energy conversion factors by social sector and by energy sort are extended from a comprehensive energy utilization conversion factor, which is estimated from the energy supply/demand balance table by sector in physical units associated with the 2007 Xinjiang input–output table.

Concerning the water requirement sub-model, the total water requirement by the whole of society is summed up as agricultural water use, industrial water use, ecological water use, and household water use. Water use by coal-related industries (i.e. coal exploitation, coal-fired power, coal-to-oil, coal-to-gas) is estimated by their output capacities and water use coefficients. Water use of other industrial sectors is estimated by an input–output model with water use intensity by sector. The water saving rate is estimated by comparing water use intensity by sector in Xinjiang and national average levels. Water use per capita was 450 m^3 in China in 2012 (China City Water Net 2013), but water use per capita in Xinjiang was 2,464 m^3, which is five times more than the national average level.

According to a local government report, in Xinjiang in 2012 (XJSLT Net 2014), the gross amount of water resources was 90.32 billion m^3, while the total water supply was 59.01 billion m^3. The total water requirement in Xinjiang in 2012 was about 59.01 billion m^3 (NBSC 2013), the agricultural water requirement was 56.17 billion m^3, the industrial water requirement was 1.24 billion m^3, the household water requirement was 1.20 billion m^3, and the ecological water requirement was 0.40 billion m^3. The agricultural water requirement in China took about a 61% share of the total water resources, but the share of the agricultural water requirement in Xinjiang was 91%, which was 30% higher than the national average level. Wastewater discharges in China took about a 30% share of the water requirement for industry and agriculture, but the share of wastewater discharges in Xinjiang was 35%, which was 5% higher than the national average level.

Household water requirement is calculated according to water use per capita. The change in ecological water requirement is assumed to be proportional to GDP growth. The local total water requirement controlling target, 515.97×10^8 m^3 in 2020 and 526.74×10^8 m^3 in 2030 (BE 2013), is set as the restriction of water resources during the entire simulation period. Developing energy industries should be coordinated with regional economic development and economic development in Xinjiang should be planned with restriction of the local total water requirement red line in the long-term future. This is the basic idea of this study.

Regarding the CO_2 emissions sub-model, total CO_2 emissions are estimated as the sum of emissions from industries and households. The choice of the carbon dioxide emissions coefficients of fossil fuel are based on an official report from the United Nations (IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006)). Eight types of energy source: coal, coke, crude oil, fuel oil, gasoline, kerosene, diesel, and natural gas are included in this model.

Input–output model

In this study, an input–output model is developed for the purpose of forecasting energy consumption, water use, and carbon dioxide emissions. The input–output model was originally developed by Professor Wassily Leontief from Harvard University, and he also created the input–output analysis method (Leontief 1990).

According to the value-based input–output table, the row balance equation is described as follows:

$$U_i = X_i - Y_i + IM_i \; i = 1,\ 2,\ \cdots\cdots,\ n \tag{1}$$

where U_i: total intermediate use of sector i; X_i: total output of sector i; Y_i: total end-use of sector i; IM_i: the imports of sector i.

This row balance equation can also be represented by a direct consumption coefficient matrix, which is described as follows:

$$AX = X - Y + IM \tag{2}$$

where A: direct consumption coefficient matrix; direct consumption coefficient a_{ij}: input from sector i due to per unit of output from sector j.

Similarly, the column balance equation is described as follows:

$$V_j = X_j - Z_j \; j = 1,\ 2,\ \cdots\cdots,\ n \tag{3}$$

where V_j: added value from sector j; X_j: total input from sector j; Z_j: final demand of sector j. This column balance equation can also be represented by the value added matrix, which is described as follows:

$$A_c X + Z = X \tag{4}$$

where $A_c = diag(\sum_{i=1}^{n} a_{i1}, \sum_{i=1}^{n} a_{i2}, \cdots, \sum_{i=1}^{n} a_{in})$, value added matrix, Z: final demand matrix, X: total input matrix.

Direct consumption coefficient of the target year is set as an initial parameter, and the RAS method is used to revise the direct consumption coefficients during each simulation period. Since the RAS method is applied to adjust the input–output table, the actual development goal of the target year can be fixed and met. Through the revision of the direct consumption coefficient matrix of the target year, the RAS method reflects the change of the direct consumption coefficient matrix under the influence of the 'substitute effect' and 'fabric effect' (Guan *et al.* 2009). To introduce substitute coefficient matrix R and fabric coefficient matrix S, direct consumption coefficient A^f of target year can be calculated as:

$$A^f = R \times A_c^b \times S \tag{5}$$

where $R = \mathrm{diag}(\mathrm{r}_1, \mathrm{r}_2, \ldots \mathrm{r}_\mathrm{n})$; $S = \mathrm{diag}(\mathrm{s}_1, \mathrm{s}_2, \ldots \mathrm{s}_\mathrm{n})$.

According to the known data such as total output in future years, total intermediate use, total intermediate inputs, and the direct consumption coefficient matrix (A_c^b) in the base year, the value of R and S can be calculated by the iterative calculation method.

Socio-economic development condition

For the prediction of carbon dioxide emissions and water use by sector, the final consumption matrix and total input of target year are calculated to gain input parameters by year. According to the relationship between disposable income per capita and economic growth, the disposable income per capita L^f of the target year can be calculated by linear fitting method (Yong & Li 2003) based on the disposable income per capita L^b of the base year. Then, the elasticity coefficient of income per capita α is introduced; here, α represents the ratio of change rate of consumption per capita to change rate of disposable income per capita. Thus, the household consumption per capita in future can be estimated as following:

$$K^f = \left(1 + \alpha \times \frac{(L^f - L^b)}{L^b}\right) \times K^b \tag{6}$$

where K^b: household consumption per capita in base year.

By introducing urbanization rate η to distinguish between urban and rural residents (Fu *et al.* 2013), rural and urban household consumption are respectively estimated as Equations (7) and (8):

$$T_u = K_u \times P \times \eta \tag{7}$$

$$T_r = K_r \times P \times (1 - \eta) \tag{8}$$

where T_u and T_r: urban and rural household consumption; K_u and K_r: urban and rural household consumption per capita; P: population; η: urbanization rate. The total household consumption T can be calculated as the sum of urban and rural household consumption, which is described as follows:

$$T = T_u + T_r \tag{9}$$

Then, the final consumption matrix of the target year can be calculated based on the share of household consumption among total end-use, which is described as follows:

$$Y = \frac{T}{\theta} \tag{10}$$

where Y: final consumption matrix of the target year; T: household consumption matrix; θ: share of household consumption among total end-use.

Then, the total input by sector of the target year can be calculated according to added value and total input by sector of the base year and the setting value of the technological progress coefficient, water saving rate, energy saving rate, and economic growth rate. The technological progress coefficient is represented by the relative change rate of value-added rate between the target year and base year and the value-added rate is the ratio of the added value by sector with the total input. Then the value-added rate of the target year can be estimated by Equation (11):

$$Z_r = R \times \frac{Z_b}{X} \tag{11}$$

where Z_r: value-added rate of target year; Z_b: added value of the base year; R: technological progress coefficient; X: total input of the base year.

Then, the total input of the predicted year can be calculated as Equation (12):

$$X_f = \frac{Z_f}{Z_r} \tag{12}$$

where X_f: total input of predicted year; Z_f : added value of predicted year; Z_r: value added rate of predicted year.

Water use sub-model

By applying the input–output table of the base year, industrial water use by sector of the target year is predicted. Taking into account living water use and ecological water use, the total water use of the whole of society in the predicted year can be calculated as Equation (13). In addition, industrial water use and living water use can be estimated, respectively, by Equations (14) and (15). Especially, ecological water use is calculated using the historical average (Cui et al. 2010):

$$W = W_i^p + W_i^R + W_i^s \tag{13}$$

where W_i^p: industrial water use, W_i^R: living water use, W_i^s: ecological water use.

$$W_i^P = \varepsilon \times N_i \times X_i \tag{14}$$

where W_i^p: industrial water use by sector i, ε: water-saving rate, N: water requirement coefficient, X_i: total output by sector i.

$$W_i^R = \vartheta \times P^f \tag{15}$$

where W_i^R: water use, ϑ: per capita water use coefficient, P^f: total population of predicted year.

The water resource constraint in the predicted year is set for scenario choice, which means the selected scenario should satisfy this condition: W $\leq$ water controlling red line.

CO_2 emissions sub-model

By using 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006), carbon dioxide emissions are estimated as the sum of industrial emissions and living emissions, which is defined as Equation (16):

$$M = M^P + M^R \tag{16}$$

where M^P and M^R: carbon dioxide emissions from industrial sector and household consumption, respectively. Both sources of CO_2 emissions can be calculated as Equations (17) and (18):

$$M^R = \xi \sum_{j=1}^{n} e_j h_j Q^R \tag{17}$$

$$M^P = \xi \sum_{j=1}^{n} e_j h_j Q^P \tag{18}$$

where ξ: average lower calorific of standard coal (kJ/kgce); e_j: carbon dioxide emission coefficients of energy type j; h_j: oxidation rate of energy type j; Q^P and Q^R: energy consumption from industrial production and household consumption, which is estimated according to the energy consumption per capita and population of the target year. Here, energy types include coal, coke, crude oil, fuel oil, gasoline, kerosene, diesel fuel, and natural gas.

The CO_2 emissions constraint in this study is set as the national planning target for CO_2 mitigation, which requires CO_2 emissions per unit of GDP in 2020 should be decreased by 40–45% compared with that in 2005.

PARAMETERS' SETTING

As mentioned above, scenario analysis of the energy industry development in Xinjiang is based on the simulation results of an integrated energy model in this study. Especially, 2007 is

Table 1 | GDP growth rate in different economic growth modes in Xinjiang (unit: %)

	High economic growth		Mid economic growth		Low economic growth	
	2014–2020	2021–2030	2014–2020	2021–2030	2014–2020	2021–2030
Total GDP	11.4	10.2	9.9	9.2	9	8.5
Primary industry	6.7	5.8	4.5	4	3.5	3
Secondary industry	12.6	11	11	10	10	9
Tertiary industry	11	10	10	9	9	9

set as the base year. The fuel emission factors used in this model are from the investigation report of CQC (i.e. China Quality Certification Centers) in China. In accordance with the economic data from the published Statistical Yearbook (XBS 2007–2013; CBS 2007–2013), the parameters of this integrated energy economic model are calibrated.

Three economic growth modes in Xinjiang are set, which are high, mid, and low rates of economic growth. GDP growth rate is set as Table 1. With continuous economic growth in Xinjiang, household consumption, disposable income per capita by urban and rural residents, and value added by sector will also be changed. Then, income elasticity with different economic growth rates can be estimated based on the changing tendency of these indicators in recent years. Disposable income per capita by urban and rural residents in future target years can also be calculated. Especially, the change of industrial value-added rate by sector can be used to simulate technological progress in Xinjiang. Then, the energy industry development, carbon dioxide emissions, and water use in each economic growth mode in Xinjiang can be predicted. The 2007 input–output table of Xinjiang, with 42 sectors, is applied in this model. The relevant data from 2007 to 2013 are available from government reports and published statistics. Parameters in this integrated energy economic model are set according to the GDP growth rate, energy industry development, and national economic growth target plan in recent years.

Three scenarios are set according to the level of low-carbon development in three economic growth modes, which are the basic scenario, water-saving and low-carbon scenario, strengthened water-saving and low-carbon scenario (Liang *et al.* 2004; Wei *et al.* 2006). Many factors such as economic development, emissions' reduction, water-saving rate, technological progress, etc., are considered in the above scenarios. By estimation of the parameters affecting these factors in these scenarios, energy consumption, carbon dioxide emissions, and water use by sector are predicted under each scenario from 2014 to 2030 in Xinjiang. Since the water-saving rate is the most important parameter in this study, it is estimated according to the difference in water consumption per unit of GDP in Xinjiang with that in other arid regions in China.

According to relevant population data in published statistical yearbooks, population growth rate and urbanization rate are set to forecast the economic scale and industrial structure in future Xinjiang. By referring to historical data of the changes of economic added value by sector, the technological progress coefficient is set (Shen & Wang 2006). Based on different patterns of economic growth, energy consumption change rate of per unit of output is set according to the relative change of energy consumption per unit of output based on the base year. The change rate of energy consumption per capita and the shares of fossil fuels in primary energy are set to simulate the changes of energy dependency and energy structure. The inter-sectoral distribution of water-saving rate is as follows: if the water-saving rate in the tertiary sector is set as 1%, then it is 2% in the primary sector, and 0.8% in the secondary sector.

Based on the recent economic situation in Xinjiang, the main parameters of each scenario in 2020 and 2030 are set as shown in Tables 2 and 3.

RESULTS ANALYSIS

Based on the policy of controlling the water requirement and CO_2 emission mitigation, how to develop a low-carbon

Table 2 | Main parameters setting in Xinjiang from 2007 to 2020

	High economic growth			Mid economic growth			Low economic growth		
	Basic Sce.	Low-carbon Sce.	Strengthened low-carbon Sce.	Basic Sce.	Low-carbon Sce.	Strengthened low-carbon Sce.	Basic Sce.	Low-carbon Sce.	Strengthened low-carbon Sce.
Technological progress coefficient	1.16	1.17	1.18	1.165	1.17	1.18	1.17	1.175	1.185
Energy consumption coefficient per unit of GDP	0.97	0.96	0.95	0.96	0.95	0.94	0.95	0.94	0.93
Share of fossil fuels in primary energy	0.90	0.88	0.86	0.91	0.89	0.87	0.92	0.90	0.88
Population (10^4 person)	2,487.2	2,487.2	2,487.2	2,487.2	2,487.2	2,487.2	2,487.2	2,487.2	2,487.2
Urbanization rate (%)	55.55	55.55	55.55	55.55	55.55	55.55	55.55	55.55	55.55
Energy consumption coefficient per capita	1.86	1.70	1.51	1.70	1.51	1.46	1.51	1.40	1.35
Water saving rate (%)	6.8	7.9	8.1	6.8	7.9	8.1	6.8	7.2	7.8

energy industry with restriction of limited water resources in Xinjiang is analyzed.

Water requirement

Water requirement for the whole of society in Xinjiang is estimated for nine scenarios, as shown in Figure 1.

First, the total amounts of water requirement in low, mid, and high economic growth modes are compared. For the enhanced water saving and low-carbon scenario in low economic growth mode, the total amounts of water requirement in 2020 and 2030 are about 52.3 and 54.9 billion m^3. For the enhanced water saving and low-carbon scenario in the mid economic growth mode, the total amounts of water requirement in 2020 and 2030 are estimated to reach 57.5 and 60.4 billion m^3. For the enhanced water saving and low-carbon scenario in high economic growth mode, the total amounts of water requirement in 2020 and 2030 are estimated to reach 60.1 and 63.0 billion m^3. It can be found that the higher the economic growth rate,

Table 3 | Main parameters setting in Xinjiang from 2021 to 2030

	High economic growth			Mid economic growth			Low economic growth		
	Basic Sce.	Low-carbon Sce.	Strengthened low-carbon Sce.	Basic Sce.	Low-carbon Sce.	Strengthened low-carbon Sce.	Basic Sce.	Low-carbon Sce.	Strengthened low-carbon Sce.
Technological progress coefficient	1.16	1.17	1.18	1.165	1.17	1.18	1.17	1.175	1.185
Energy consumption coefficient per unit of output	0.96	0.95	0.94	0.95	0.94	0.93	0.94	0.93	0.92
Share of fossil fuels in primary energy	0.86	0.84	0.82	0.87	0.85	0.83	0.90	0.89	0.88
Population (10^4 person)	2,838.00	2,838.00	2,838.00	2,838.00	2,838.00	2,838.00	2,838.00	2,838.00	2,838.00
Urbanization rate (%)	68.38	68.38	68.38	68.38	68.38%	68.38%	68.38%	68.38%	68.38%
Energy consumption coefficient per capita	1.92	1.65	1.57	1.86	1.75	1.68	1.82	1.73	1.65
Water saving rate (%)	6.1	7.2	7.5	6.3	7.3	7.5	6.3	6.5	6.7

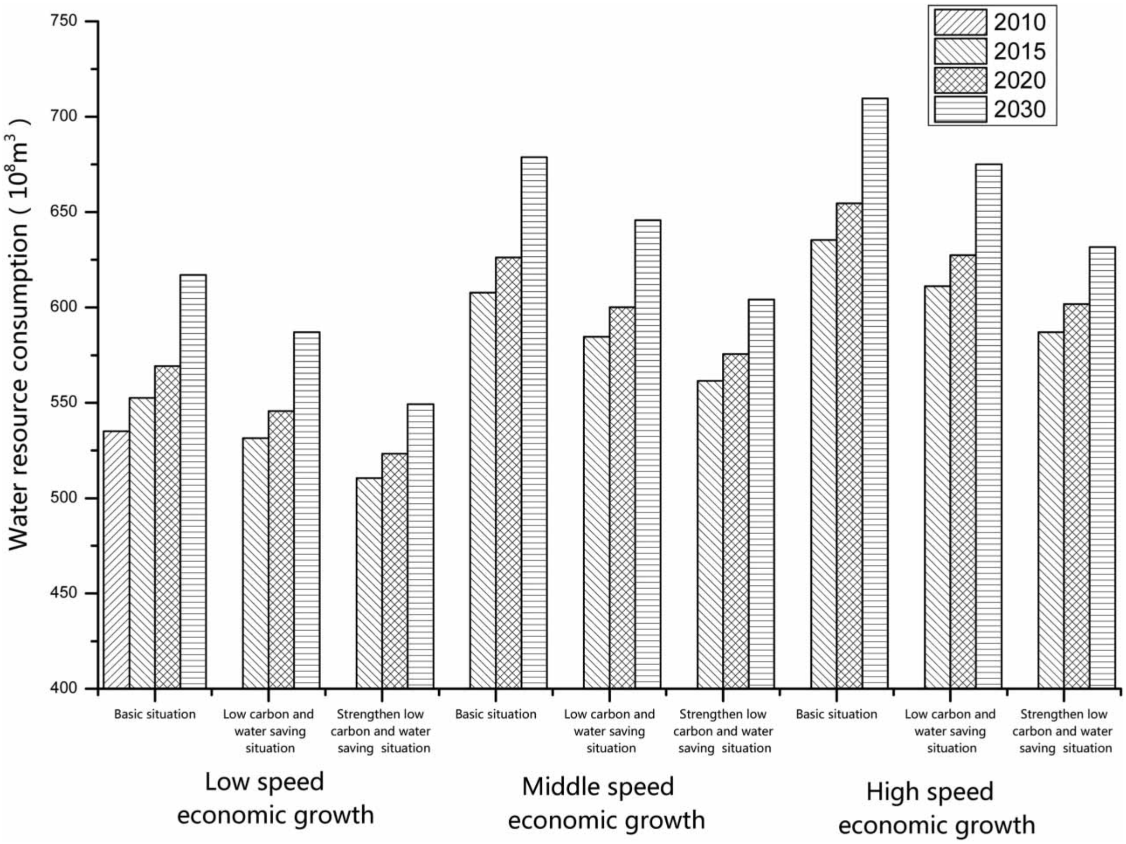

Figure 1 | Water requirement for the whole of society in Xinjiang.

the more water use will be needed. Meanwhile, the water saving rate in each economic growth mode is also differently set for three scenarios according to the levels of technological progress. Obviously, a higher water saving rate is set for the enhanced water saving and low-carbon scenario, while a lower water saving rate will be used for the normal water saving and low-carbon scenario or basic scenario. Even with the same economic growth rate, water saving rate and energy saving rate in each scenario, water use shows an upward trend with continuous economic growth. Even for the enhanced water saving and low-carbon scenario in low economic growth mode, water use in 2020 and 2030 still cannot be controlled below the total water requirement red line (i.e. 51.6 and 52.7 billion m^3) under the premise of not squeezing agricultural water use. If Xinjiang cannot achieve the great expectations of water saving, the economic development of Xinjiang will be unsustainable.

Undoubtedly, the water use of secondary industries (especially for energy industrial sectors) will rise with economic development in Xinjiang. For all the above scenarios, water use of energy industrial sectors shares over 30% of total water use of secondary industries. For the enhanced water saving and low-carbon scenario in low economic growth mode, water use of secondary industries will reach 1.42, 1.67, and 2.87 billion m^3, while water use of the energy industrial sector will reach 0.47, 0.53, and 0.95 billion m^3, respectively, in 2015, 2020, and 2030. For the energy industrial sectors, the promotion of advanced water saving technology is imperative. Of course, the constraints of water resources should also be taken into account for specific energy industry development planning.

With the restriction of limited water resources, water saving is a strategic approach for sustainable economic development in Xinjiang. Since the energy industry includes high water consuming technologies such as coal-to-gas, coal-to-oil, and coal-fired power, to study the scientific and reasonable development scale of each technology for the energy industry in Xinjiang seems particularly important.

In fact, the most stringent water management regulation began to be implemented in 2013. According to Water Resources Bulletin in Xinjiang in 2011 (XJSLT Net 2011), only 80.36 billion m^3 of water storage existed in Xinjiang. The total amounts of available water supply in Xinjiang in 2020 and in 2030 are estimated as respectively 51.6 and 52.7 billion m^3. However, water use in the mid and high economic growth modes has exceeded the total water requirement red line. Only in the low economic growth mode can the requirement to keep the total water requirement red line be met.

As shown in Figure 2, the amounts of water use by sector appear as increasing trends from 2015 to 2030 for three scenarios in the low economic growth mode, but in each target year water use can be greatly reduced in two low-carbon scenarios compared to that in the basic scenario. In fact, water use by primary industry (agricultural water requirement) accounted for the largest share of the total water requirement, which is more than 90% in 2013. With the promotion of water saving technology, agricultural water requirement in Xinjiang has a large reduction potential. If effective water-saving measures can be adopted, the shortage of water resources for energy industry development can be eased. The water requirement for the strengthened water-saving and low-carbon scenario in low economic growth mode still cannot be controlled under the total water requirement red line in Xinjiang. But it has been close to the red line standard and lower than the current water supply amount. Therefore, this scenario can be selected for analysis of the development of energy base construction in Xinjiang.

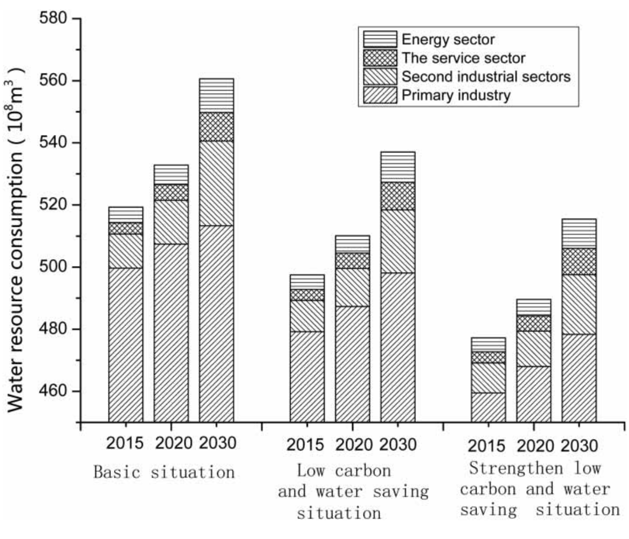

Figure 2 | Water requirement by sector in Xinjiang for three scenarios in low economic growth mode.

Undoubtedly, the economic growth of Xinjiang will depend upon the acceleration of developing secondary industry, especially the energy industry. Thus, the water requirements of secondary industry and energy industry need to be paid extra attention. The water requirement share of the secondary industry and energy industry among the total water requirement for the strengthened water-saving and low-carbon scenario in low economic growth mode is shown in Table 4. Energy industry in this study includes the coal exploitation, oil and gas industries, petroleum processing industry, coking and nuclear fuel processing industries, electricity, heat production and supply industries, and gas production and supply industries, etc. Even in this scenario, industrial water requirement still shares a very small proportion of the total water supply in Xinjiang. Moreover, the energy industry consumes over 30% of the water requirement of secondary industry. The share of industrial water requirement among the total water requirement of the whole of Xinjiang seems to have an upward trend, which increases from 2.54% in 2010 to 5.23% in 2030. The share of the energy industry's water requirement also increases from 0.86% in 2010 to 1.73% in 2030.

Such a water requirement structure is consistent with the government program of economic development in Xinjiang. Due to regional characteristics of the industrial structure in Xinjiang, the government will accelerate the construction of an energy industry base in Xinjiang during

Table 4 | Water requirement structure for strengthened low-carbon and water saving scenario in low economic growth mode from 2010 to 2030 in Xinjiang

	2010	2015	2020	2030
Secondary industry				
Water requirement (10^8 m^3)	13.6	14.2	16.7	28.7
Share	2.54%	2.78%	3.19%	5.23%
Energy industry				
Water requirement (10^8 m^3)	4.6	4.7	5.3	9.5
Share	0.86%	0.92%	1.01%	1.73%
Ratio	33.82%	33.10%	31.74%	33.10%

the 13th five-year-plan period. The continuous growth of the energy industry and its related water requirement will contribute to economic development in Xinjiang. Obviously, the development of the energy industry in Xinjiang will be restricted by the limited water resources.

Developing advanced water-saving technology in the coal-related industry chain seems particularly imperative. Of course, the restriction of water resources should also be taken into account when planning the development scale of the energy industry in Xinjiang. For the strengthened water-saving and low-carbon scenario in low economic growth mode in 2020 Xinjiang, the production scale of coal mining will reach about 285 million tons, and the scale of generation of coal-fired power will reach up to 250 billion kWh. Regarding the coal chemistry industry, its production capacity will reach 1.338 million tons of oil and 13.93 billion m^3 of coal gas in 2020. But in 2030, the scale of production of coal mining more appropriately amounts to around 552 million tons, the scale of generation of coal-fired power may be up to 300 billion kWh, and the production capacity of coal chemistry could reach 2,057,200 tons of oil and 19.43 billion m^3 of coal gas. Due to the huge water use factors of the coal-to-oil and coal-to-gas industries, their production scale should not be too large under conditions of limited water resources in Xinjiang. However, coal-fired power technology has become mature, and its environmental impacts have been reduced to be relatively small. Moreover, it can have a lower water use factor than coal chemical technologies, thus coal-fired power technology should serve as the main form of coal utilization in Xinjiang.

Carbon dioxide emissions

Similar to the water requirement, energy consumption and CO_2 emissions by sector are also simulated by the integrated energy economic model in this study. Energy consumption, CO_2 emissions, and CO_2 intensity for three scenarios in three economic growth modes in 2020 and 2030 Xinjiang are shown in Tables 5 and 6.

Obviously, the total CO_2 emissions appear as a constantly upward trend in Xinjiang. The total CO_2 emissions were 198.39 million tons in Xinjiang in 2010. For the strengthened water-saving and low-carbon scenario in low economic growth mode, the total CO_2 emissions in Xinjiang will be increased by 52.97% in 2020, and 105.28% in 2030. However, CO_2 emissions per unit of GDP appear as a gradual decline. CO_2 emissions from the electricity, heat production and supply sectors, chemical and petroleum processing sectors, coking and nuclear fuel processing sectors for the strengthened water-saving and low-carbon scenario in low economic growth mode are increased more than other sectors for the three scenarios in the three economic growth modes.

Table 5 | Energy consumption, CO_2 emissions, and CO_2 intensity in 2020 Xinjiang

	High economic growth	Mid economic growth	Low economic growth
Basic scenario			
Energy consumption (Mtce)	149.61	147.31	146.03
CO_2 emissions (Mt)	335.71	326.56	314.20
CO_2 intensity (tons/10^4 Yuan)	2.32	2.44	3.05
Low-carbon and water saving scenario			
Energy consumption (Mtce)	143.82	140.26	138.16
CO_2 emissions (Mt)	323.05	314.76	311.48
CO_2 intensity (tons/10^4 Yuan)	2.24	2.35	2.95
Strengthened low-carbon and water saving scenario			
Energy consumption (Mtce)	141.41	138.08	132.67
CO_2 emissions (Mt)	314.09	306.41	302.48
CO_2 intensity (tons/10^4 Yuan)	2.18	2.29	2.87

Table 6 | Energy consumption and CO_2 emissions in 2030 Xinjiang

	High economic growth	Mid economic growth	Low economic growth
Basic scenario			
Energy consumption (Mtce)	232.23	203.26	188.71
CO_2 emissions (Mt)	551.37	475.60	431.51
CO_2 intensity (tons/10^4 Yuan)	1.58	1.98	2.13
Low-carbon and water saving scenario			
Energy consumption (Mtce)	225.77	198.24	187.61
CO_2 emissions (Mt)	536.47	443.97	424.39
CO_2 intensity (tons/10^4 Yuan)	1.53	1.95	2.10
Strengthened low-carbon and water saving scenario			
Energy consumption (Mtce)	221.67	191.65	186.48
CO_2 emissions (Mt)	521.58	429.66	417.26
CO_2 intensity (tons/10^4 Yuan)	1.50	1.90	2.06

In this study, it is estimated that carbon dioxide emissions per unit of GDP in Xinjiang in 2010 reached 3.65 tons/10^4 Yuan. CO_2 emissions per unit of GDP in Xinjiang in 2020 will be reduced by 21.6% compared with that in 2010, and it will be decreased by 43.6% in 2030 compared with that in 2010. In this study, CO_2 emissions per unit of GDP in 2010 are estimated to be reduced 8.9% compared with that in 2005. Thus, compared with that in 2005, CO_2 emissions per unit of GDP in Xinjiang in 2020 will be reduced by 28.6% for the strengthened water-saving and low-carbon scenario in low economic growth mode. Obviously, the CO_2 emissions constraint cannot be satisfied even under the more strict energy-saving scenario, which requires CO_2 emissions per unit of GDP in 2020 should be decreased by 40–45% compared with that in 2005.

Therefore, CO_2 emissions in Xinjiang promote a serious situation, which should cause concern for the government. Especially, energy saving and emission reduction should be stressed in the coal-related industry chain. Low water use and a low-carbon industrial structure should also be promoted in Xinjiang. Finally, the demonstration of carbon capture and sequestration technologies should also be developed.

Coal industry development

Under the red line constraints of total water requirements, development scale and related water use of various coal exploitation and utilization schemes for the strengthened water saving and low-carbon scenario in low economic growth mode are simulated. There are three coal exploitation and utilization schemes in this scenario. Case 1 is the 'inner demand driven' scheme, which means the energy industry in Xinjiang only needs to satisfy its own energy demand. Case 2 is the 'equilibrium development' scheme, which means reasonably considering coal and related production can be outward transported, and coal utilization includes coal-fired power generation, coal-to-oil and coal-to-gas. Case 3 is the 'all for power generation' scheme, which means coal exports in Xinjiang are all substituted by coal-fired power generation and electricity transmission. This means that coal utilization only includes coal-fired power generation, and coal chemical industries are strictly forbidden considering the high water use of coal-to-oil and coal-to-gas technologies. The development scale of coal exploitation and utilization is forecast as shown in Table 7.

Table 7 | Production capacity of coal exploitation and utilization in 2020 and 2030 Xinjiang

	Coal exploitation (10^6 tons)	Coal-fired power (10^9 kWh)	Coal-to-oil (10^4 tons)	Coal-to-gas (10^8 m^3)
2020				
Case 1	248	123		
Case 2	285	250	133	139
Case 3	320	401		
2030				
Case 1	508	162		
Case 2	552	300	205	194
Case 3	602	520		

The production of coal exploitation in 2015 Xinjiang is estimated at about 219 million tons. The production of coal-fired power generation in 2015 Xinjiang is estimated at about 110 billion kWh. In case 1 of the 'inner demand driven' scheme, the production of coal exploitation in Xinjiang will be increased by 13.24% and 131.96% in 2020 and 2030 and the production of coal-fired fired power generation will be increased by 11.81% in 2020 and 47.27% in 2030. In case 2 of the 'equilibrium development' scheme, the production of coal exploitation in Xinjiang is estimated to be increased by 30.14% in 2020 and 152.05% in 2030. The electricity produced by coal-fired power technology will be increased by 127.27% and 172.73% in 2020 and 2030. The production capacity of coal-to-oil and coal-to-gas in 2020 and 2030 are forecast according to the government energy development program. In case 3 of the 'all for power generation' scheme, the production of coal exploitation in Xinjiang will be increased by 46.12% and 174.89% in 2020 and 2030. The electricity produced by coal-fired fired power technology will be increased by 264.55% in 2020 and 372.73% in 2030. However, the ability of outward transportation of coal will be limited by the speed of construction of railway and transportation; the ability of electricity outward transmission will be limited by the speed of construction of the ultra-high voltage grid and transmission capacity. Undoubtedly, the speed of such infrastructure facilities' construction is set according to government reports.

Table 8 | Water requirement of coal exploitation and utilization in 2020 and 2030 Xinjiang (unit: 10^8 m^3)

	2020			2030		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Energy industry	5.3			9.5		
Coal exploitation	2.23	2.56	2.87	4.32	4.69	5.11
Coal-fired power	0.37	0.76	1.22	0.50	0.93	1.61
Coal-to-oil		0.13			0.18	
Coal-to-gas		0.71			1.04	

The water requirement of coal exploitation and utilization schemes in Xinjiang is shown in Table 8. Water requirement coefficients of various coal exploitation and utilization technologies in this study are selected according to a consulting research report in China (Huang *et al.* 2014). From the view of coordinated and continuous development, the water requirement of coal exploitation and utilization is better to be shared at about 45–50% among the energy industry. Due to the huge water use of coal-to-oil and coal-to-gas, the growth of coal-to-oil and coal-to-gas should not be too fast within the limited water resources. In this study, the scale of coal-to-gas in 2020 is estimated according to the production capacity of a complete production line, whose water requirement is close to the total water requirement of coal-fired power generation in case 2. Thus coal-to-gas is not suitable to be developed in Xinjiang, and coal-to-oil also cannot be developed quickly. In case 3 of the 'all for power generation' scheme, the water requirement can be well controlled. As is well known, coal-fired power technology has become highly mature, while its environmental impacts and related water use are relatively smaller. Thus, coal-fired power technology should be used as the main way of coal utilization in Xinjiang.

CONCLUSION

Based on the above analysis of simulation results, the scale of development and speed of growth of the energy industry in Xinjiang should be controlled with the restriction of water resources, especially for high water consuming energy projects such as the coal chemicals related industrial chain. Compared with coal export, coal-fired power technologies can be powerfully promoted for outward electricity transmission from Xinjiang. Since water saving is the guarantee of economic growth in Xinjiang, the importance of water saving measures should be stressed. To fulfill the task of reducing carbon intensity and energy intensity, energy saving and carbon reduction in high energy consuming industrial sectors such as the electricity and heat sectors, chemical sector and oil processing sector should be strengthened.

In terms of energy forecasts and modeling, energy production capacity for such as coal mining, coal gasification, and coal-fired power are estimated by the consideration of their related water use according to a potential analysis of the energy industry. Energy-related carbon dioxide emissions from industrial sectors in Xinjiang are also forecasted. Especially, the choice of the water saving rate unavoidably affects the accuracy of simulation results. Finally, low-carbon technology of energy industry development in Xinjiang is chosen among several scenarios. In our future research, this integrated energy economic model should be further revised and developed by combining multi-objective optimization methods with an input–output model.

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