Water–energy nexus in Shaanxi province of China

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ABSTRACT

Synergistic effects between water and energy policies are still not fully considered in Shaanxi province of China. To address the challenges of water scarcity and growing energy demand, the water–energy nexus of Shaanxi is investigated in this paper by input–output analysis (IOA). The findings indicate that water and energy resources are interdependent on each other. It is observed that agricultural water use intensity is 0.28 m^3 per USD and industrial water use intensity is at the lowest level of 0.013 m^3. Therefore, there is a huge water saving potential in the agricultural sector. Owing to the high energy consumption in agricultural irrigation, reducing irrigation water is of benefit both for water saving and energy conservation in the agricultural sector. Meanwhile, the industrial sector accounts for 63.8% of total energy consumption in Shaanxi, and it is urgent to change the economic structure to service-based rather than agricultural or industrial activities. It is believed that integrated strategies and planning are more favored in the future in Shaanxi. Water use limitation, energy mix adjustment and pricing mechanisms should be involved in water and energy policy formulation. Remarkably, because of being low carbon and water saving, the natural gas industry will become increasingly promising in the following decades.

Key words | input-output analysis (IOA), integrated strategies, Shaanxi, synergistic effects, water–energy nexus

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INTRODUCTION

Water and energy are the key resources recognized as indispensable inputs to economic and population growth. By 2050, water and energy demands are projected to increase by 55% and 80% globally (Loeb 2016). However, these two resources are increasingly in short supply (Carrillo & Frei 2009; Hussey & Pittock 2012). Environmental problems and resource crisis will come out, which will threaten economic growth and human survival. If we want more water, we need energy. Similarly, if we need more energy, we should have an abundance of water to produce it (Schnoor 2011). In 2010, 15% of global water has been employed in energy production. The two resources are intertwined and the water–energy nexus is getting more attention. By definition, the water–energy nexus describes the relationship between water and energy. It is attracting more researchers who love to explore better and integrated measures to resolve the resources crisis (Zhang & Anadon 2013; Zhang *et al.* 2014). Previous studies are focused on two aspects, including water use in energy production and energy consumption in the water system. Nowadays over 20% of total world fresh water flows into the energy sector (Webber 2011; Bidoglio & Brander 2016; Chini *et al.* 2016). For instance, much water is used for drilling and fracturing in oil and gas exploration. Power conversion and biofuel production also need considerably large amounts of water (Hadian & Madani 2013; Zhang & Anadon 2013). If we consider water when using energy, it will decrease their utilization. Hence, a better understanding of the energy–water nexus is critical, and integrated polices and plans are badly needed.

Shaanxi, a province in the northwest of China, belongs to the inland semi-dry climate, a district poor in water

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resources. In Shaanxi, soil erosion problems and land desertification are serious, leading to the fragile environment (Shen *et al.* 2015). Meanwhile, as the Energy and Chemical Industry Base, Shaanxi has the duty to supply energy for other provinces in China. The high intensive exploitation of coal and other energy resources consume a large quantity of water, making the original fragile environment worse. Because of inadequate water resources and large-scale coal mining, serious pollution and lowering of levels of groundwater have appeared, which is restricting economic development (Fan 2005). In order to achieve sustained economic and social development in Shaanxi, more attention should be focused on water and energy security.

Zhang & Anadon (2013) distinguish water withdrawal and water consumption, and they consider that water consumption equals water withdrawal minus wastewater discharge. In this study, water use refers to the water resources used by individuals, industry or other users, containing the water consumed and water discharged. To draw robust qualitative insights about the water–energy nexus in Shaanxi, this paper evaluates the relationship between the two resources based on an input–output model. The paper contains four parts. The second introduces the input–output analysis (IOA), including the processing methods and data sources. The third section investigates the overall utilization of water and energy resources in Shaanxi, followed by the analysis of the energy–water nexus to reflect the relationship between these two resources. The fourth and fifth sections provide the conclusions and policy implications for resources management within the economic system. By our findings, we attempt to explore resources sustainability and provide some new insights for relieving water scarcity and energy conservation in Shaanxi, and even in China.

MATERIALS AND METHODS

Input–output analysis

IOA is employed to investigate the completed water and energy use for every sector of Shaanxi in 2012 (Table 1). According to the triple division of industry regulations, in this paper, the original 42 sectors in the input–output table are aggregated into 17 sectors (seen in the Appendix, available with the online version of this paper).

Based on the IOA, the following steps can be adopted to assess water use and energy consumption.

The direct requirement coefficients matrix A is demonstrated by Equation (1):

$$A = [a_{ij}]; \quad a_{ij} = \frac{X_{ij}}{X_j} \tag{1}$$

where a_{ij} indicates the direct input from sector i to sector j ($i,\ j \le n,\ n = 17$). Then, the Leontief inverse matrix B is expressed as:

$$B = [I - A]^{-1} = [b_{ij}] \tag{2}$$

where b_{ij} indicates the gross input from sector i, necessary for the per monetary unit of final demand in sector j. The direct water intensity submatrix is shown as in Equation (3):

$$DWI = [DWI_1, DWI_{2,\ldots,}DWI_n], \quad DWI_j = \frac{W_j}{X_j} \tag{3}$$

where DWI_j is the direct water intensity in sector j, W_j represents the water use in sector j, and X_j is the gross output in sector j. The total water use matrix is determined as shown

Table 1 | Structure of input–output table of Shaanxi

Input/output		Intermediate use: Sector 1	Sector 2	…	Sector n	Total use: Export	Sum	Gross output
Intermediate input	Sector 1	X_{11}	X_{12}	…	X_{1n}	EX_1	Y_1	X_1
	Sector 2	X_{21}	X_{22}	…	X_{2n}	EX_2	Y_2	X_1
	…	…	…	…	…	…	…	…
	Sector n	X_{n1}	X_{n2}	…	X_{nn}	EX_n	Y_n	X_n
Gross input		X_1	X_2	…	X_n			

in the following equations:

$$TWI_j = DWI_j \times [I - A]^{-1} = DWI_j \times b_{ij} \quad (4)$$

$$TWI = [TWI_1, TWI_{2,\ldots,} TWI_n] \quad (5)$$

$$TW = [TW_1, TW_{2,\ldots,} TW_n], \quad TW_j = TWI_j \times Y_j \quad (6)$$

where TWI_j is the total water intensity in sector j. TW_j denotes the total water use in sector j. Y_j is the aggregated final use in sector j.

The same procedure is applicable for energy use.

Data sources

Four groups of data are used in this paper, and they are listed in Table 2.

RESULTS AND ANALYSIS

Water and energy resources in Shaanxi

Water availability and use

In Shaanxi, the total water supply of 2012 is 8.8 billion m³. Surface water supplies account for 61.4% of the total water supply, and groundwater is 37.9%. There are four supply sources for surface water, including reserve water, channel water, draw water and artificially ferried, with the proportions of 21.9%, 26.9%, 12.5% and 0.1%.

Agricultural water covers a large share of total water use. Irrigation water is 4.96 billion m³ with 56.3%. The proportions of industrial, municipal, household and ecological water use are 9.8%, 15.1%, 13.9% and 4.9% respectively. In 2012, the three industries value-added are 20.55, 121.05 and 75 billion USD respectively. Combined with water use in the three industries, the paper points out that the water efficiency in agriculture is the lowest and the second industry is the highest.

It is significant to further investigate water usage in every sector (shown in Table 3), Obviously, the major water user is the agricultural sector with 4.76 billion m³. The next is construction, for which the water resource is 2.82 billion m³. With the fast expansion of the economy and urbanization, more buildings are desired to satisfy the residents' living. This will lead to more demand for raw materials and energy in construction, resulting in further large water demand. With economic development, the water use of sectors is in flux and this reflects the changes of industrial structure in Shaanxi. For energy sectors, mining consumes a great deal of water resource, and much water is poured into energy extraction and processing (mining and washing of coal, extraction of petroleum and natural gas). Production and supply of electricity, heat, gas and water require 0.24 billion m³ of water resources.

Table 2 | Data for the assessment of water use and energy consumption in Shaanxi

Data groups	①	②	③ = ①*②	Sources
Water	Water-use quota of sector Water intensity (Mielke et al. 2010)	Sectoral outputs Nine major energy products	Water use in sector j Water requirement for energy production	Published academic literature; Statistics of Shaanxi Province (2013)
Energy	Energy intensity for every stage of water value chain (Siddiqi & Anadon 2011)	Water supply in every stage of water value chain	Energy use for water value chain	
	Energy production and consumption data for energy use in sector j			Statistics of Shaanxi Province (2013)
IO table	Monetary IO table of Shaanxi for 2012 (the latest year with data available)			Statistics of the People's Republic of China (2013)
Others	Three industries value-added; water and energy supply; water and energy use mix; energy trade			Statistics of Shaanxi Province (2013)

Table 3 | Total water use of sectors in Shaanxi in 2012 (billion m³)

Sectors	Water use
Agriculture	4.76
Mining	1.04
Food, beverage and tobacco	1.76
Textile and garment	0.91
Timber processing and furniture	0.10
Paper manufacture	0.24
Chemical industry	0.68
Non-metallic mineral industry	0.22
Metal manufacture	1.28
Machinery manufacture	0.65
Transportation equipment	0.71
Communication and electronic equipment	1.00
Other manufacture	0.07
Production and supply of electricity, heat, gas and water	0.24
Construction	2.82
Commercial and transportation	0.66
Other services	1.38
Households	0.71

Energy availability and use

In 2012, the total proven energy resources of Shaanxi have reached 25.9 billion tons of coal equivalent (tce), 67.84% of which is coal resources, ranking third in China. In the energy supply, coal resources account for 73.6%. The second is oil resources with 15.9% and natural gas is 8.02%. The total energy generation capacity is 0.4 billion tce in 2012. Over 60% of coal and natural gas are exported externally from Shaanxi. Through in-depth analysis, the major energy resources have a higher generation capacity than consumption, so the extra energy resources have been exported to other regions. As the major energy export province, Shaanxi's economic development is largely promoted by the energy economy. However, the unique coal-dominated energy structure will increasingly induce serious ecological and environmental problems, which will affect the sustainability of the economy and society.

There is 0.1 billion tce in energy resources applied for economic activities and residents' living. Based on the IO table, energy consumption in every sector is estimated (five major energy products are listed in Table 4). It shows that coal consumption in each sector is far more than any other energy. Construction, mining and chemical product sectors have the higher energy consumption. A little energy resource is consumed in paper manufacture, as well as in agriculture.

Water–energy nexus

Water requirement for energy production

The energy sector is one of the biggest water users in China, only second to the agricultural sector. From fossil fuel extraction, refining, to electricity generation, water resources are needed in the whole energy value chain. According to the

Table 4 | Total energy use of sectors in Shaanxi in 2012 (million tce)

	Coal	Coke	Gasoline	Diesel oil	Electricity
Agriculture	5.57	0.17	0.18	0.75	0.85
Mining	39.85	1.26	0.23	0.80	2.81
Food, beverage and tobacco	8.65	0.27	0.23	0.68	1.01
Textile and garment	5.06	0.13	0.08	0.24	0.98
Timber processing and furniture	1.07	0.03	0.02	0.05	0.32
Paper manufacture	3.65	0.11	0.05	0.11	0.49
Chemical industry	33.01	0.66	0.22	0.62	1.71
Non-metallic mineral industry	4.39	1.53	0.04	0.11	0.66
Metal manufacture	25.61	8.91	0.22	0.62	3.85
Machinery manufacture	13.46	2.56	0.22	0.57	2.39
Transportation equipment	16.38	2.78	0.25	0.67	2.12
Communication and electronic equipment	18.68	2.47	0.28	0.72	2.47
Other manufacture	0.41	0.06	0.01	0.02	0.11
Production and supply of electricity, heat, gas and water	14.94	0.11	0.03	0.08	1.12
Construction	75.30	8.86	1.13	3.88	8.94
Commercial and transportation	19.41	0.53	2.94	7.61	2.81
Other services	24.28	1.06	0.42	1.10	2.99
Households	1.70	/	1.35	0.11	1.82

finding of Mielke *et al.* (2010) (Table 5), we evaluate water use in the energy production of Shaanxi. Mielke *et al.*'s finding shows the water demand per energy product, and the total water can be calculated from the per product water demand multiplied by the energy consumption in Shaanxi.

For all kinds of energy resources, Table 5 and Figure 1 show that electricity generation needs more water than the others. In Shaanxi, electric power originates from hydropower, thermal power, wind power and solar power. The thermal power occupies the biggest share, which is 93%. Because of the coal-powered thermal power, large amounts of water are devoted to coal extraction and processing, contributing most of the water use in electricity. Hydropower accounts for 6.5% of total electric power, and 5–25 m^3 water is used for every megawatt-hour (MWh), which is higher than other power-generating approaches. However, owing to the low carbon emissions, hydropower is more favored. Several studies also show that compared with traditional coal-fired power generation, 229 g carbon can be reduced in hydropower generation for every MWh, which is friendly to the environment (Gerbens-Leenes *et al.* 2009). Kerosene production, fuel oil production and natural gas

Table 5 | Water use for energy production in Shaanxi in 2012

	Water intensity (gal/MMBtu) ①	Energy products (million MWh) ②	Water use for energy production (million m^3) ③ = ①*②	Share of total water use (%)
Coal	0–8.57	2,785.62	0–90.36	0–0.4
Coal washing	4.29–15.71	316.07	5.13–18.80	0.02–0.09
Crude oil production	7.14–75.71	410.26	11.09–117.57	0.05–0.6
Gasoline production	45–108.57	88.36	15.05–36.31	0.07–0.2
Kerosene production	45–108.57	3.69	0.63–1.52	0
Diesel production	45–108.57	109.31	18.62–44.92	0.09–0.2
Fuel oil production	45–108.57	7.19	1.22–2.95	0–0.01
Natural gas production	0–5	307.71	0–5.82	0–0.03
Electricity generation	2.7	133.05	359.24	1.87
Total			410.98–677.5	2.14–3.52

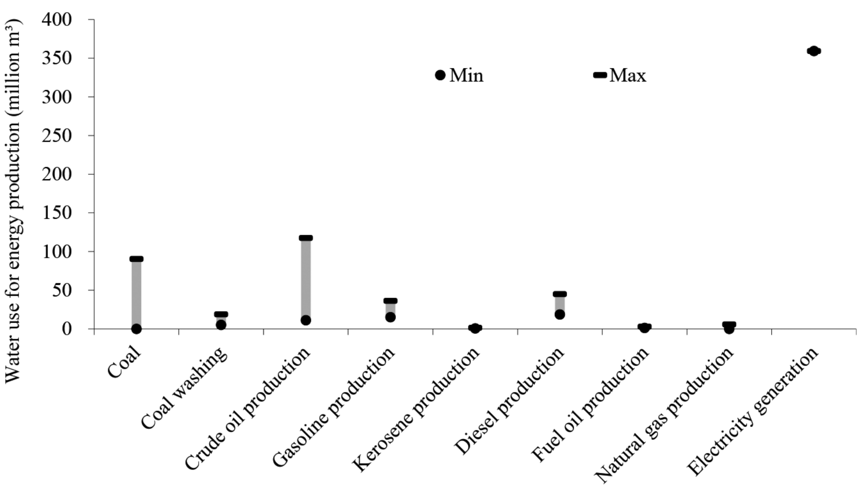

Figure 1 | Water use for energy production in Shaanxi.

production require a little water. Water use in crude oil production varies substantially, and is always affected by geography, geology, technique and reservoir depletion.

Energy requirement for the water value chain

Every stage of water production requires energy: abstraction, conveyance, treatment, distribution and disposal. And it is investigated in this paper approximately (Table 6 and Figure 2), including the minimum and maximum values based on the findings of Siddiqi & Anadon (2011).

Water abstraction: In the abstraction period, most energy is used for groundwater abstraction. From the perspective of energy demand per unit water abstraction, there is much more energy needed for pumping groundwater than using gravity-based water conveyance from a surface source (Siddiqi & Anadon 2011). In Shaanxi, groundwater accounts for 37.9% of the total water supply. In recent years, the groundwater level has been falling in Shaanxi, and the energy consumption of groundwater abstraction has been increasing. In the meantime, an increase in pump lift by an average 1 metre would cause carbon emission rates

Table 6 | Energy use for different stages of the water value chain in Shaanxi in 2012

		Energy intensity (kWh/m^3) ①	Water supply (0.1 billion m^3) ②	Energy use in water value chain (10000 tce) ③ = ①*②	Share of total energy use (%)
Abstraction	Groundwater	0.16–0.7	33.42	6.57–30.08	0.06–0.3
	Surface water	0.02	54.01	1.33	0.01
Conveyance	Rural area	0.38	58.19	27.18	0.27
	Urban area	0–3.7	29.85	0–135.73	0–1.36
Treatment	Surface water	0.4	54.01	26.55	0.27
Distribution	Urban area	0.18–0.78	29.85	6.6–28.61	0.06–0.29
Disposal	Discharge: wastewater	0–0.04	11.25	0–0.55	0–0.01
	Wastewater collection and treatment	0.3–1.2	6.3	2.32–9.29	0.02–0.09
Total				70.56–258	0.7–2.58

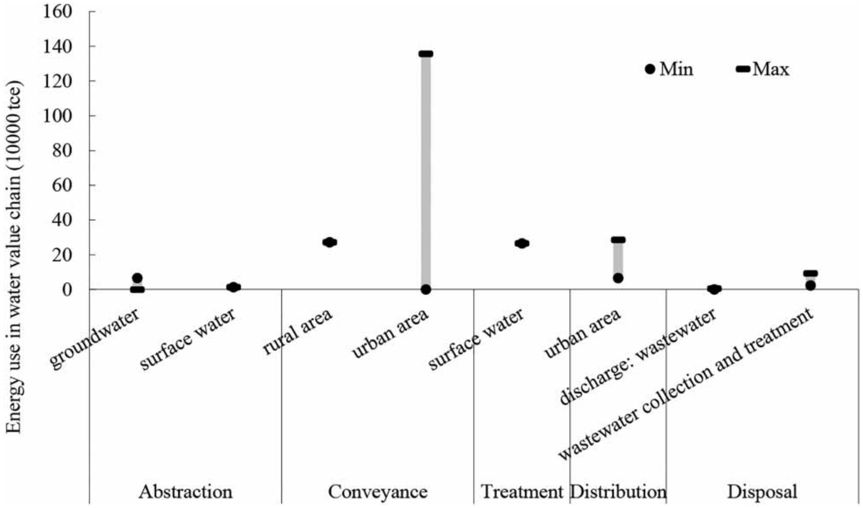

Figure 2 | Energy use for different stages of the water value chain in Shaanxi.

to rise by around 2%, so measures must be taken to manage the groundwater resource and reduce the abstraction of the groundwater resource. With that, it will be beneficial for energy saving and emission reduction (Li *et al.* 2013).

Water conveyance: Table 6 and Figure 2 show that the largest part of energy consumption is devoted to water conveyance. In Shaanxi, much water is provided through channeling and artificially ferried driven by power, leading to quantities of energy consumption (Fang *et al.* 2015). Agricultural water occupies 66% of the conveyed water and the rest is conveyed in the urban system. In rural areas, the irrigation efficiency is less than 50%, resulting in inefficient water use and serious water waste. In order to meet the irrigation water demand, more water should be conveyed to supply the irrigation districts to make up the water loss. This will bring about extra energy consumption for water conveyance. Recently, several water-saving techniques (such as sprinkler irrigation and drip irrigation) have been adopted gradually in Shaanxi, which are with very little water, but higher in energy consumption.

Water treatment: Another energy-intensive source is water treatment in Shaanxi. Water treatment means to remove some matter (harmful to production and life) from the water with physical, chemical and biological measures. For the specific use of water, the water treatment techniques contain filtration, coagulation, flocculation, corrosion inhibition, scale inhibition and other processes. In Shaanxi, water treatment is aimed at surface water, so the enormous energy demand is only for surface water treatment.

Water distribution: Generally, water distribution is mainly concentrated on urban supply networks, through long pipelines powered by energy. In Shaanxi, the penetration of urban water is 96.15% and the water supply pipe system spreads all over the city, therefore, 0.06 to 0.28 million tce is used for water distribution in the urban system.

Water disposal: In 2012, there is 1.13 billion m^3 wastewater, and 0.63 billion m^3 water is collected for disposal. With the wastewater data and the per unit energy use of wastewater disposal, we estimate that energy consumption for water disposal ranges from 0.02 to 0.1 million tce in 2012. In comparison with other water processes, water disposal uses less energy. Furthermore, different levels of treatment and technologies result in different energy requirements.

The interconnection between water and energy

In China, water use and energy consumption are highly interconnected and complementary (Gu *et al.* 2016). For Shaanxi, a 0.1 billion tce rise in energy consumption will induce a 1.5 billion m^3 increase in water use. In the water sector, a large amount of energy flows into water conveyance. And in energy sectors, electricity generation has the highest water requirement, which accounts for 50% of total water use in energy production (Figure 3).

RECOMMENDATIONS AND POLICY IMPLICATIONS

Combining our findings with the status of the water–energy nexus, some recommendations are put forward for sustainable development in Shaanxi.

Trade implications

As the major energy export region, a great deal of virtual water embodied in energy products flows into other regions from Shaanxi, and reducing water-intensive product export is vital for water conservation. Based on our observation, electricity and crude oil export increase the virtual water outflow. Therefore, substitution or export control will be useful for alleviating the water pressure. Certification and labeling of embodied water and energy use on all products will have the same benefits.

Re-thinking supply and demand

From a resource standpoint, there is wide variation in supplies of water and energy. Because of strategic trade in virtual water and energy, it is possible that resource reallocation will take place across sectors. Changing the economic structure to service-based rather than agricultural or industrial activities will enable existing supplies of water to remain sufficient.

Because of the huge divergence of water use during the whole energy production, water saving could be achieved by adjusting the energy mix and promoting the use of low-water technology. The results show that kerosene, fuel oil and natural gas production need little water. Globally, of the

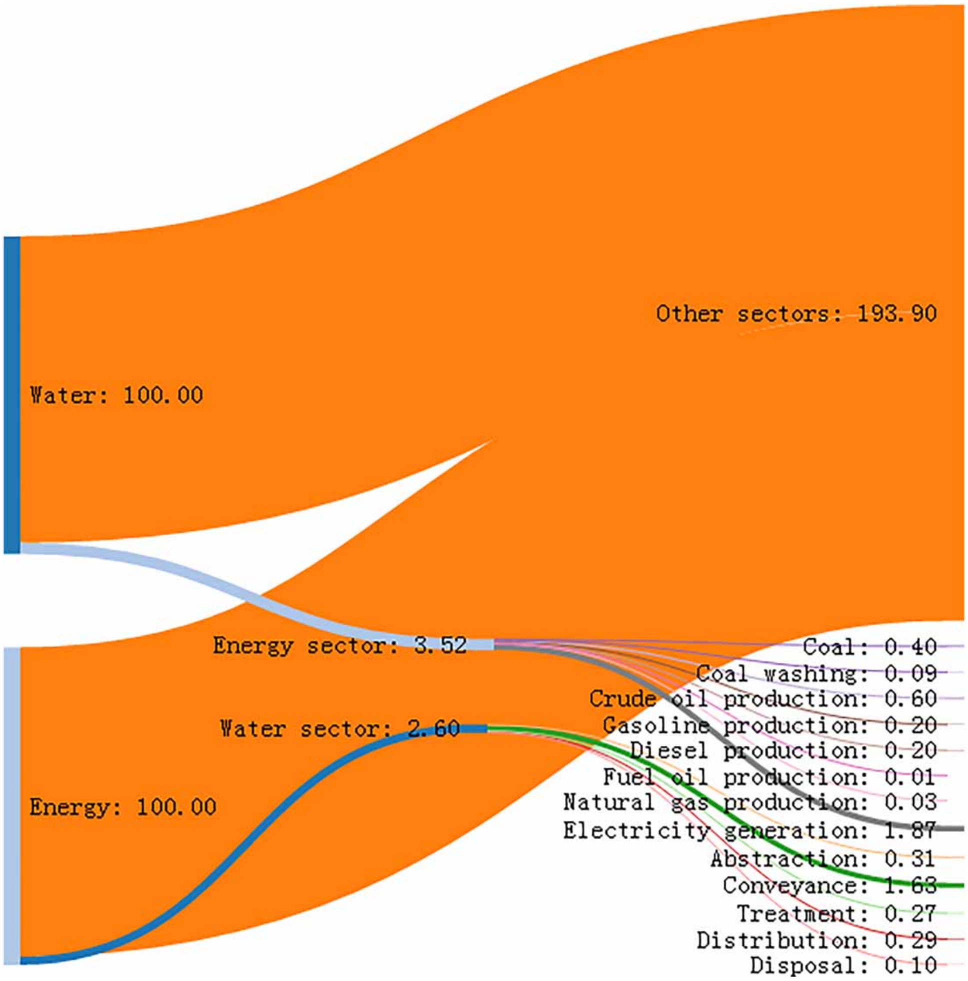

Figure 3 | Interconnection between water and energy in Shaanxi.

traditional fossil fuels, natural gas has the higher calorific value and heat utilization efficiency. Generation efficiency of electrical power by natural gas will be improved by 50%. Currently, global gas-fired electricity is growing rapidly with an average annual increase rate of 6.8% after 1990. Generating the same amount of power from natural gas combined-cycle power plants would consume 0.25 gal kWh^{-1}, a 60% reduction versus coal (Grubert *et al.* 2012). As more coal-fired power plants retire due to age and/or regulatory compliance costs, a more explicit shift from coal to natural gas could begin, especially given today's historically low natural gas prices. By 2050, natural gas will occupy 37% of world energy and be the primary fuel, larger than oil and coal (Makogon *et al.* 2007). Meanwhile, carbon emission from natural gas consumption is half that of coal, so increasing the proportion of natural gas supply is crucial for adjusting the energy mix and developing the energy industry into taking less water.

Policy and plan implications of the water–energy nexus

Fee collections and technology promotion are major approaches to resource saving in the water–energy nexus.

Considering the present status of the legal system for energy production and water conservation in Shaanxi, there are no other synergistic laws and regulations on energy and water resources but the compensation mechanism of soil and water conservation in energy development. However, there exist some issues in the compensation mechanism, such as an un-established mechanism and low standard for the existing compensation (Zhang 2008). In view of the background of energy and water use, establishing and improving compensation fees for water use and wastewater discharge in energy development is efficient in reducing water use.

In addition, technology promotion is another measure for resource conservation in Shaanxi. The implementation of 'coal mining under water-containing condition' is an urgent technical problem to be solved in energy production. Much efficient and sustainable mining technology should be put forward.

CONCLUSION

In this paper, we carry out the comprehensive assessment of water use in energy production and energy consumption in the water value chain in Shaanxi based on IOA.

The results above show that there is a larger water-saving potential in agricultural irrigation than in other sectors. In addition, the industry sector accounts for 63.8% of energy consumption. Therefore, service sectors will be the favored economic activities in future.

For the water–energy nexus in Shaanxi, water abstraction occupies most of the energy consumption and the abstraction approaches have to be improved to save energy. In the case of making new energy plans and policy, there should be emphasis on natural gas utilization, which consumes less water. In the light of international experience, more concern should be focused on the gas-fired electricity industry in Shaanxi, which is helpful for reducing the water use of coal-fired power and optimizing energy structure. Above all, in order to keep the balanced development of resources, water and energy use deserve to be considered in policy formulation simultaneously.

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