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Structure Dynamics and Risk Assessment of Water-Energy-Food Nexus: A Water Footprint Approach

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Abstract: The "Water-Energy-Food Nexus" is one of the present research hotspots in the field of sustainable development. Water resources are the key factors that limit local human survival and socioeconomic development in arid areas, and the water footprint is an important indicator for measuring sustainable development. In this study, the structural dynamics and complex relationships of the water-energy-food system in arid areas were analyzed from the perspective of the water footprint, and the risk characteristics were evaluated. The results show that: (1) Agriculture products and livestock products account for the largest water footprints (>90%), which is much higher than the water footprints of energy consumption (<5%). From the water footprint type, the blue water footprint (>50%) > the grey water footprint (20%–30%) > the green water footprint (<20%). (2) Since 2000, especially after 2005, while energy consumption drove rapid economic growth, it also led to the rapid expansion of the water footprint in the Manas River Basin. By 2015, the water deficit was relatively serious, with the surface water resource deficit reaching 16.21×10^8 m^3. (3) The water-energy risk coupling degree of the water-energy-food system in this basin is comparatively significant, which means that it is facing the dual pressures of internal water shortage and external energy dependence, and it is vulnerable to global warming and fluctuations in the international and domestic energy markets. Thus, it is necessary to adjust the industrial structure through macroeconomic regulation and control, developing new energy sources, reducing the coupling degree of system risks, and achieving sustainable development.

Keywords: water-energy-food; water footprint; structure and dynamics; risk assessment; the Manas River Basin

1. Introduction

1.1. Water-Energy-Food Nexus

Water, energy, and food (WEF) are indispensable resources for human survival and important limiting factors for regional development [1]. As a separate field of research, these three major issues have been very deeply studied [2–6]. In recent years, the systemic risks of food, energy, and water resources have become increasingly prominent and thy have received great attention from governments and academic circles [7]. In January 2011, the World Economic Forum published the "Global Risk

Report (sixth edition)" and, for the first time, the "Water-Energy-Food Nexus" (WEF Nexus) risk group was listed as one of the three major risk groups in that year [8]. In November of the same year, the German Federal Government convened an international conference on the WEF Nexus security in Bonn. It proposed that food, energy, and water resources are complex interconnected systems. Research needs to be carried out from the perspective of grouping rather than isolation in order to explore the development path of green economy [9]. Since then, research on the WEF Nexus has become a research hotspot of various research institutions [10,11]. The reason why "nexus" is used to describe the complex relations among the three is that they are either explicit or implicit, direct or indirect, which makes it difficult to describe in a general language.

Although the definition of WEF Nexus is still affected by the research scale and development target period, an understanding of the different perspectives of WEF Nexus is gradually taking shape [12]. In recent years, quantitative studies of the three items have begun to emerge in this field. For example, De et al. [13] proposed a collaborative management method for food, energy, and water resources across river basins from the perspective of water resource protection. Vora et al. [14] quantified the virtual irrigation water volume in the process of food interstate trade in the United States, and then further calculated the implicit energy consumption in virtual irrigation water. Sherwood et al. [15] calculated food production in cities in the United States and energy and water consumption in the three production sectors and compared their spatial differences. These studies have promoted detailed and quantitative research on the WEF system and emphasized the importance of prioritizing water resources. For a region or river basin, water-energy-food is a complex system that is related to social, economic, environmental, ecological, and other systems, which has a multi-center complex network and a large number of feedback loops and local characteristics. Different regions have different characteristics of resources and models of socioeconomic development, which cannot be generalized, but researchers can gain insight from corresponding theory or methods.

At present, the research is still in its infancy, focusing on the qualitative description of the relationship between water, energy, and food, the quantification of the relationship, and the construction of the related platforms. However, there are still some shortcomings: the existing research has paid more attention to the quantitative calculation of the correlation between each pair of items and the related management measures [16,17], lacking the quantitative study of the three items as a whole system, and the research methods that are based on smaller scales, such as watershed level, are relatively immature.

1.2. Theory of Virtual Water and Water Footprint

Tony Allan initially defined concept of virtual water [18] as "the amount of water needed to produce agricultural products", and then expanded the definition to "the amount of water needed to produce goods and services". It is materialized in virtual form in products, also known as "embedded water" or "exogenous water". Virtual water strategy refers to the purchase of water-intensive agricultural products (especially food) from water-rich countries or regions through trade to obtain water and food security. Virtual water strategy has become a strategic means for water-scarce countries and regions to balance water deficiency and an effective regulatory measure to alleviate water crisis [19].

Based on virtual water research, Hoekstra [20] further proposed the concept of water footprint in 2002 to characterize the impact of human consumption on water resources. The water footprint is derived from the concept of the ecological footprint and it is defined as the amount of water that is needed for all products and services consumed by a known population (a country, region, or individual) for a certain period of time [21]. The concept of the water footprint links physical water with virtual water, which is described by the sum of regional water consumption and virtual water net import. It reflects a new idea of evaluating the real consumption of national or regional water resources. In human consumption of water resources, the proportion of domestic water (physical water) is usually small, and most of the consumption is reflected in the form of virtual water, which is the main component of the water footprint.

Currently, research on virtual water and water footprints mostly focus on the water footprint of crops [22], while research regarding energy water footprints is relatively limited [23]. For a basin that is based on agriculture, the WEF Nexus is a necessary measure to change water resource management from basin management to problem management, which is a new stage of water resource management after integrated water resource management (IWRM) and adaptive water management (AWM) [24].

1.3. Necessity of Combination of WEF-Nexus and Water Footprint

Water resources and food are the basis for the survival and development of oasis in arid regions, while energy is the lifeblood of economic development. There are many interdependent, synergistic, and restrictive trade-offs between the two resources, and both are also important indicators and rulers for the sustainable development of local natural and social economy. Energy system and water system are closely linked, but energy policy and water resources policy are separately formulated. Long-term separate management makes the conflict between the two resources increasingly prominent [25]. More and more top journal articles are beginning to focus on the issue of collaborative management of energy and water. Liu et al. [26] took bioenergy and virtual water as research objects, and considered that the potential social, economic, and environmental impacts of the two resources need to be analyzed by the system integration method. Agriculture is a major water user. There are great potential resource pressure and ecological risks in developing irrigated agriculture in oasis. Oasis in inland river basin is a relatively independent, fragile, and sensitive ecosystem. The coupling effects of food, energy, and water can be reflected by water footprint, which indicates the sustainability of the socioeconomic-ecosystem in an arid region.

In view of this, and when considering the importance of water resources in arid areas, this paper attempts to introduce virtual water theory into the WEF system. Taking the Manas River Basin in arid areas of Northwest China as the research object, we analyzed the resource utilization structure and social economy development of typical basins in 2000–2015 from the perspective of water footprint and evaluated WEF risks, including internal and external risks, to provide references for local sustainable development.

2. Study Area

The Manas River Basin is located in the inland arid area of northwest China (Figure 1a), with a latitude of 43°27′–45°21′N and longitude of 85°01′–86°32′E. It is bordered by the Tianshan Mountains in the south and the Gurbantunggut Desert in the north [27]. The basin area is 2.2×10^4 km^2. The terrain inclines from south to north, with an altitude of 200–5000 m. The landscape pattern is mountain, plain, and desert from south to north (Figure 1b), which belongs to the typical "mountain-oasis-desert" system in arid areas [28]. The average annual temperature is 6.6°C; the average annual precipitation is approximately 200 mm in the oasis area; and, it can reach 600–700 mm in the mountain area. The precipitation is mainly concentrated in June to September. The average annual runoff is 2.3×10^9 m^3 [29]. The Manas River is the largest river in the basin and the average annual runoff is 1.3×10^9 m^3. The abundance of light and heat resources and good climatic conditions are conducive to the development of agricultural and livestock production [30].

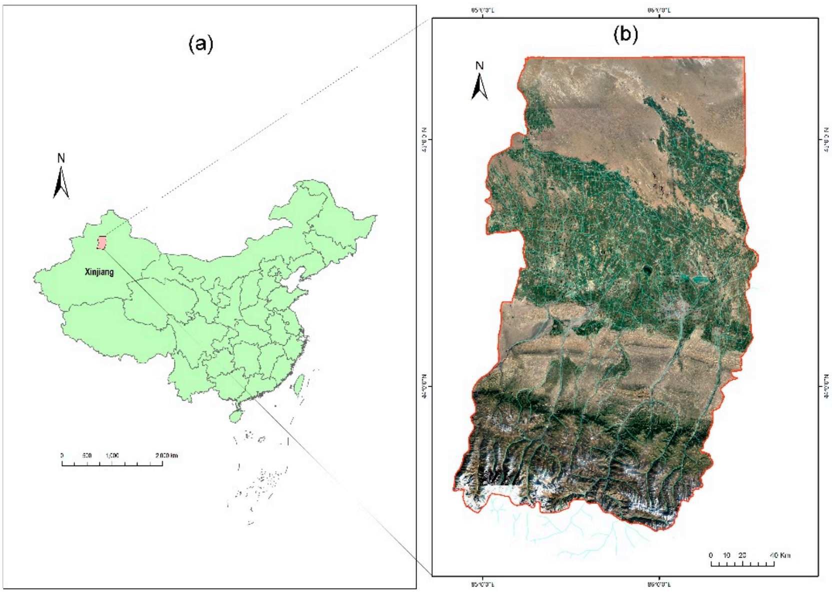

Figure 1. Location (**a**) and landscape overview (**b**) of the Manas River Basin.

In social and economic terms, the Manas River Basin includes Shihezi City, Manas County, and Shawan County. In 2015, the total population of the basin was 103.43 × 10^4 people and the GDP was 71.78 billion yuan RMB. The Manas River Basin is a typical agricultural and pastoral region. Animal husbandry is mainly concentrated in the grasslands of the upper and middle reaches. Livestock are mainly herbivorous animals, such as cattle and sheep, and omnivores, such as pigs and poultry. Sheep are mainly natural grazing, while cattle and pigs are mainly concentrated in captivity. The planting industry is mainly concentrated in the plain area of the downstream oasis. In the early stage (before 2000), "grain was the key link". Later, due to the obvious benefits of cotton production, it gradually changed to "make cotton as the key link". By 2010, the area that was planted in the reclamation area was 19.13 × 10^4 hm^2, of which cotton was 14.37 × 10^4 hm^2, accounting for 75.1%. Crops 2.09 × 10^4 hm^2, only 10.9%, vegetables 1.24 × 10^4 hm^2, accounting for 6.5%, of which 0.99 × 10^4 hm^2 of processed tomatoes, 0.9 × 10^4 hm^2 of various types of fruit, forming a planting production structure that was dominated by "cotton, grain, fruit and vegetables" [31]. At present, the basin has become the largest oasis farming area in Xinjiang and the fourth largest irrigated agricultural area in China [32]. Industrial products in urban areas are mainly agricultural byproducts (food industry, textile industry), chemical products (fertilizers, pesticides, plastics, etc.), building material products (cement and electrolytic aluminum, etc.), and energy-consuming products (raw coal, electric power, thermal power, etc.).

3. Materials and Methods

3.1. Data Sources

The meteorological data in this article were obtained from the China National Meteorological Website (http://data.cma.cn/). The hydrological data were collected from the Xinjiang Water Resources Department and the Manas River Basin Administration. The calculation parameters of crop water footprint referred to the data that were recommended by Food and Agriculture Organization of the United Nations (FAO) (http://www.fao.org/land-water/databases-and-software/crop-information/en/). Agricultural and livestock production data and energy consumption data were collected from the Statistical Yearbook of local cities and counties (Shihezi City, Manas County, and Shawan County) from 2000 to 2015.

According to the actual situation of production development in the Manas River Basin, combined with relevant research results [33], in order to show the overall water use situation of industrial and agricultural production in the basin, this study chose cotton, maize, and wheat as the main crop products; meat (including beef, mutton and pork), milk, and eggs as the main livestock products; and, coal, electricity, and heat as the main energy sources. The relevant data are easier to obtain and unify from the statistical yearbook of city and counties. Table 1 showed the main productions and consumptions of agricultural, animal husbandry, and industry statistics of the Manas River Basin from 2000 to 2015 for every five years. Combined with meteorological data, the virtual water content and water footprint can be calculated. In order to make sure the virtual water content is reasonable, we compared different researches about the virtual water content of crops in arid areas, and considered the actual water consumption of agricultural production in this basin.

Table 1. Changes of productions of main crops and livestock and consumptions of main energy sources in the basin.

Year	Cotton	Maize	Wheat	Meat	Eggs	Milk	Coal	Electricity
2000	27.33	14.05	17.12	5.73	2.23	4.30	246.82	48.58
2005	36.95	17.73	11.62	8.39	3.35	15.01	478.92	57.09
2010	46.16	35.40	26.53	15.27	5.17	30.18	1271.17	148.16
2015	74.55	54.44	20.10	20.19	6.00	45.27	2548.69	445.11

[1] The unit of crops and livestock productions is 10^4 t; the unit of coal consumption is 10^4 tce; the unit of electricity is 10^8 kw·h. [2] The data in the table were collected and summarized by the statistical yearbooks of Shihezi City, Manas County and Shawan County.

3.2. Water Footprint Calculation and Risk Assessment Methods

3.2.1. Calculation of Virtual Water and Water Footprint of Crop Products

The CROPWAT 8.0 software that was developed by Joss Swennenhuis for the water resources development and management service of FAO, and the related parameters that were recommended by FAO mainly calculates the virtual water of crop products. Since cotton, maize, and wheat are the main crops in this area, this paper only discusses these three crops. The evapotranspiration of the reference crop (ET_0) can be calculated using the monthly maximum daily temperature and minimum daily temperature, daily average relative humidity, daily average wind speed, and sunshine hours observed by local meteorological stations in 2000, 2005, 2010, and 2015, and then multiplied by the corresponding crop coefficients in each growing period of crops. The theoretical water demand of crops (ET_C) can be obtained.

The virtual water content of a crop is the ratio of the water requirement of crops (ET_C) to the yield per unit area of the crop, i.e., the amount of water that is needed to produce per unit mass crop products. The calculation equation is as follows:

$$D = 10 \times ET_C \ / \ Y_0 \tag{1}$$

where D is the virtual water content of the crop (m^3/kg), ET_C represents the water requirement of the crop in the growth period (mm), and Y_0 is the crop yield per unit area (kg/hm^2).

According to the virtual water consumption per unit crop yield and the total crop yield, the regional water footprint of crop production (WFC) can be calculated. The equation is as follows:

$$WFC = D \times Y_T \tag{2}$$

where WFC is the water footprint of the crop production (m^3), D is the virtual water consumption per unit mass of crops (m^3/kg), and Y_T is the total crop yield in the region (kg).

The water footprint of crops can be divided into the green water footprint (WFC_{Green}), the blue water footprint (WFC_{Blue}), and the grey water footprint (WFC_{Grey}) on the basis of the source and destination of crop water consumption [34–37]. The green water footprint is the effective precipitation that was consumed by crops during the growth period, the blue water footprint is the effective irrigation water consumed during the crop growth period, and the grey water footprint indicates the amount of water needed to dilute the pollution of surface water or groundwater caused by fertilization, pesticide spraying and other activities to the natural background level. The water footprint of crop production should theoretically be equal to the sum of the green water footprint, blue water footprint, and grey water footprint (Equation 3). Because drip irrigation under membranes has been widely used in this area, the field utilization coefficient of irrigation water is relatively high, and the pollution degree of surface water and groundwater is very limited, so the grey water footprint is not considered here.

$$WFC = WFC_{Green} + WFC_{Blue} + WFC_{Grey} \tag{3}$$

where WFC is the total water footprint of the crop and WFC_{Green}, WFC_{Blue}, and WFC_{Grey} are the green, blue, and grey water footprints of the crop, respectively. The allocation of water footprints is related to precipitation and soil conditions during crop growth.

3.2.2. Calculation of Virtual Water and Water Footprint of Livestock Products

The water footprint of livestock products refers to the amount of water that is consumed in raising livestock and the production process of livestock products. Livestock products mainly refer to live animal products and livestock-processed products. Among them, the virtual water content of an animal's living body depends on the total amount of water consumed during its whole growth process, including the virtual water content of fodder consumption, drinking water, and water consumption of other health services [38]. The virtual water content of livestock products depends on the livestock type, the feeding status during the growth of the livestock, and the geographic location in which the livestock product is produced [39]. In this paper, referring to the relevant literature [40–44], and when combined with the actual local situation, the virtual water content of beef, lamb, pork, eggs, and milk was given as 16 m^3/kg, 8 m^3/kg, 6 m^3/kg, 3.5 m^3/kg, and 2.2 m^3/kg, respectively.

Since most of the animal husbandry is mainly centralized breeding, most of the feed ingredients are from local agricultural products, such as straws of wheat and maize and seeds of cotton. To avoid double counting, the water footprint of the livestock products was converted by 50%, i.e., the water footprint from the fodder planting part was deducted.

3.2.3. Calculation of Virtual Water and Water Footprint of Energy

The water footprint of energy refers to the pollution and consumption of water in the process of energy production. Since energy production does not involve plant growth processes, its green water footprint does not need to be considered. In the production of coal-based fuels, a large amount of water is consumed and a large amount of wastewater is generated. The primary energy consumption in this area is mainly coal-based fuels (coal, coke, and diesel), and the secondary energy, such as electricity and heat, are mainly produced by coal-based fuel conversion through thermal power generation. Therefore, this paper mainly considered the blue water footprint and grey water footprint of coal-based fuel production and its power conversion. According to the relevant research results [45], the virtual water content per unit mass of raw coal is 11.71 kg/kgce, of which 2.15 kg/kgce is blue water and 9.56 kg/kgce is grey water. The virtual water per unit of electricity is 14.06 kg/kw·h, of which blue water is 3.49 kg/kw·h and grey water is 10.57 kg/kw·h.

3.2.4. Structural Risk Assessment of the WEF System Based on Water Footprint

To quantify and evaluate the risk of sustainable development in this basin, three risk indicators were chosen in this study: internal risk indicator, external risk indicator, and comprehensive risk indicator. The internal risk indicator was characterized by internal water resources pressure, the external risk indicator was characterized by external energy dependence, and the comprehensive risk indicator was characterized by the water-energy risk coupling degree. It should be noted that the "energy" here specifically refers to traditional nonrenewable energy sources, such as coal and petroleum. Since the WEF system is a complex nonlinear system, the risk and coupling degree inside and outside the watershed WEF system are only explained in general. It is generally considered that a strong coupling degree of water energy utilization leads to a great structural risk for the system. The relevant risk indicator algorithm are as follows:

$$\text{WPI} = \text{WDL} / \text{WSC} = \text{WF} / \text{NRW} = \text{WF} / \text{SR} \tag{4}$$

where WPI is the internal pressure of water resources, WDL is the water demand level, WSC is the water supply capacity, WF is the regional water footprint, NRW is the regional natural renewable water resources, and SR is the annual surface runoff of the basin.

$$\text{EDI} = \text{EI} / \text{EC} = (\text{EC} - \text{ES}) / \text{EC} \tag{5}$$

where EDI is the external dependence of energy, EI is the energy import, EC is the energy consumption, and ES is the local energy supply.

$$\text{WER} = R^2\ (\text{WPI}, \text{EDI}) \tag{6}$$

where WER is the risk coupling degree of water and energy and R^2 is the goodness of fit of the regression equation.

4. Results

4.1. Structural Characteristics of the Water Footprint of the Basin WEF System

The agriculture of the Manas River Basin is dominated by planting and supplemented by animal husbandry. The primary industry dominated by agriculture and animal husbandry plays an important role in the social production of the basin and is a basic industry. Among them, the planting industry is the largest, and cotton, maize, and wheat are the main crops. As an important cotton production base in Western China, the cotton planting area accounts for approximately 80% of the local planting area, and its water consumption is also the largest; the whole agricultural water consumption accounts for more than 90% of the total water consumption in the basin.

Due to natural grassland conditions, animal husbandry in the basin is also relatively developed. The livestock are mainly cattle, sheep, and pigs. With the continuous development of the social economy, the scale of livestock breeding is also expanding. A considerable part of the water footprint of the livestock industry comes from feed production and processing, followed by the grey water footprint that is caused by cleaning up houses and treating the excrement of livestock and poultry (approximately 30% of the total water footprint), and the proportion of livestock and poultry drinking water is relatively small and basically negligible.

Energy imports and agricultural product exports mainly comprise the Manas River Basin. Energy consumption mainly comes from the secondary industry, including manufacturing and processing industries and construction industries, which account for more than 90% of the total energy consumption of production activities and living in this region. The energy structure is mainly based on coal, electricity and heat. Coal is mainly dependent on external imports and it is mainly used for coal-fired power generation, while electricity and heat are generated by local thermal power plants. Taking Shihezi city as an example, coal consumption accounts for approximately 80% of the total energy consumption, while electricity and thermal energy consumption are close to 20%. As time went by, thermal power consumption was gradually replaced by the consumption of electric power resources. The blue water and grey water footprints of coal mining and coal-electricity conversion were mainly included in the energy water footprint mainly.

Figure 2 shows the water footprint distributions in the main industries and the water footprint type structures in the Manas River Basin. From the distribution of the water footprint, agricultural products have the largest water footprint, accounting for 60%–80% of the total water footprint, followed by livestock products, accounting for 20%–30% of the total water footprint, and energy consumption has the smallest water footprint, accounting for less than 5%. From the perspective of water footprint type, the water footprint of the basin is dominated by the blue water footprint, which accounts for more than 50% of the total water footprint, followed by the grey water footprint and the green water footprint, where the green water footprint varies due to the changes of annual precipitation, and is generally less than 20%, while the grey water footprint is generally increasing, reaching approximately 30%.

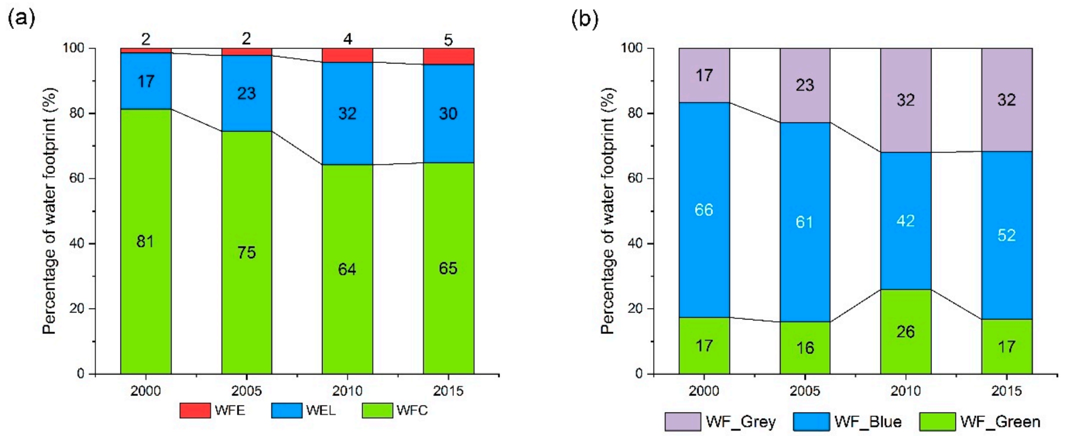

Figure 2. Distribution and structure of water footprint in the Manas River Basin, where (**a**) Water footprint proportions of major crop products (WFC), livestock products (WFL) and energy consumption (WFE); and, (**b**) Proportions of the green water footprint (WF_Green), the blue water footprint (WF_Blue), and the grey water footprint (WF_Grey).

4.2. Changes and Dynamics of Water Footprint in the WEF System of the Basin

4.2.1. General Change of Water Footprint of the Basin

From 2000 to 2015, the changes in the production water footprint of crop and livestock products and the consumption water footprint of energy consumption in the region are shown in Table 2 and Figure 3. The water footprints of crops, livestock products, and energy, as well as the total water footprint of the river basin, are increasing year by year. The annual runoff of the basin is basically in a relatively stable state. The runoff in 2000 and 2010 was larger, while the runoff in 2005 and 2015 was smaller. When compared with the annual runoff of the basin, the total water footprint of the Manas River Basin in 2000 was smaller than the annual runoff, which means that the water resources were relatively sufficient. In 2005, it reached a critical point, that is, the total water footprint and the total runoff were basically equal. After that, the water footprint of the basin continued to increase, showing a water deficit, especially in 2015, when the water footprint of the basin reached 41.75×10^8 m^3, while the annual runoff of the basin was only 25.54×10^8 m^3 and the surface water resource deficit reached 16.21×10^8 m^3.

Table 2. Water footprint changes of the Manas River Basin from 2000 to 2015 ($\times 10^8$ m^3).

Year	WFC	WFL	WFE	WFT	SR	WD
2000	15.08	3.19	−0.35	17.92	27.22	−9.30
2005	18.08	5.64	−0.63	23.09	23.41	−0.33
2010	21.19	10.41	−1.62	29.98	27.65	2.33
2015	30.52	14.21	−2.98	41.75	25.54	16.21

[1] WFC: water footprint of crop products. [2] WFL: water foot print of livestock products. [3] WFE: water footprint of energy consumption. [4] WFT: total water foot print. [5] SR: surface runoff. [6] WD: water deficit.

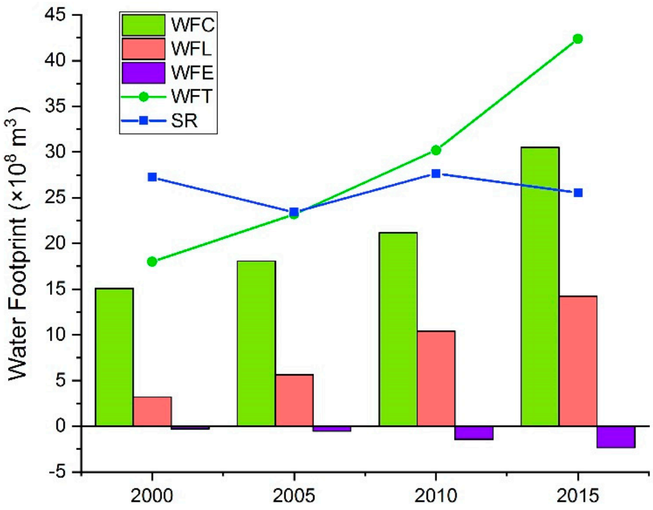

Figure 3. General changes of water footprint in the Manas River Basin from 2000 to 2015.

Certainly, a considerable amount of the gray water footprint was included, which may not necessarily result in actual water consumption, but if not considered, then it will lead to increasingly serious water pollution. For example, in 2015, after deducting 30% of the grey water footprint from the total water footprint, there was still a 4.13×10^8 m^3 blue water gap that could only be met by pumping groundwater. Moreover, the ecological water demand has not been considered in this case. If the minimum 23% ecological water demand of the basin was deducted from the annual runoffs, then the water deficit would be even larger [46,47]. In fact, the natural ecological water consumption of Xinjiang was only approximately 1% of the renewable surface water resources in 2015, which may result in the serious degradation of natural ecosystems [48].

4.2.2. Water Footprint Changes of Main Crop Products

From 2000 to 2015, the planting area in the Manas River Basin expanded by 1.9 times, growing from 26.1×10^4 hm^2 to 49.7×10^4 hm^2. As a result, the water footprint of crops doubled (Table 3). Figure 4 shows the changes in the virtual water and water footprints of the main crops in the Manas River Basin from 2000 to 2015. The water footprint was dominated by cotton because the virtual water consumption and planting area were both the largest among those crops. With the popularization of water-saving irrigation technology, such as drip irrigation under the membrane, water use efficiency and cotton yield continuously improved, significantly decreasing the virtual water consumption of cotton, which reduced the pressure of irrigation water use to some degree. However, due to the continuous expansion of the planting area and the improvement of crop yield, the total water footprint continues to rise rather than decline. Wheat and maize are the main food crops, which take comparatively little water footprint but account for a large part of the water footprint of livestock products.

Table 3. Changes of virtual water and water footprints of the main crops in the Manas River Basin.

Year	Virtual Water (m^3/kg)			Water Footprint ($\times 10^8$ m^3)			
	Cotton	Wheat	Maize	Cotton	Wheat	Maize	WFC
2000	4.5	1.0	0.6	12.40	1.78	0.91	15.08
2005	4.3	1.0	0.7	15.72	1.15	1.21	18.08
2010	3.6	0.9	0.6	16.67	2.49	2.04	21.19
2015	3.3	1.2	0.6	24.84	2.32	3.37	30.52

[1] WFC is the total water footprint of crops.

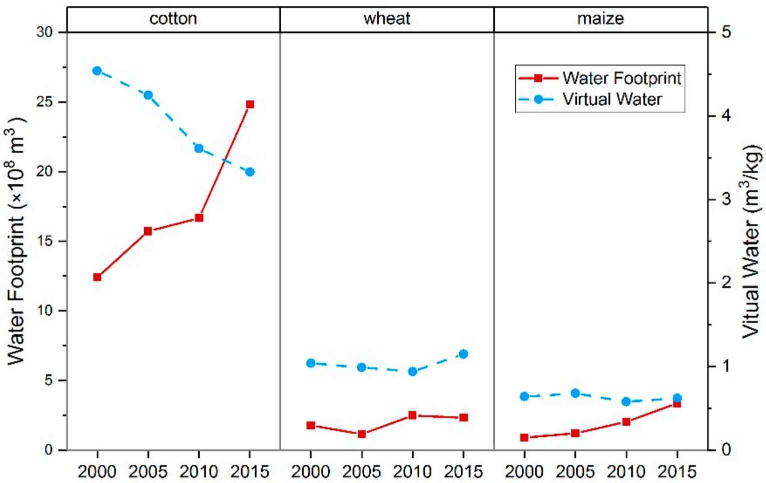

Figure 4. Changes of the virtual water and water footprints of the main crops.

4.2.3. Water Footprint Changes of Main Livestock Products

Figure 5 shows the changes in the water footprint of livestock products, especially the meat products of the basin. The total water footprint also increased rapidly from 2000 to 2015 (expanding approximately 4.5 times), with the production of meat, eggs, milk, and other livestock products increasing by three to four times. Meat products consume the largest water footprint (accounting for approximately 63% of the total water footprint of livestock products), followed by milk products (accounting for approximately 28% of livestock products). When comparing the water footprints of different meat products, it was found that the proportions of pigs, cattle, and sheep were basically the same before 2005. After that, Shihezi City expanded the scale of pig breeding, thus significantly increasing the water footprint of animal husbandry.

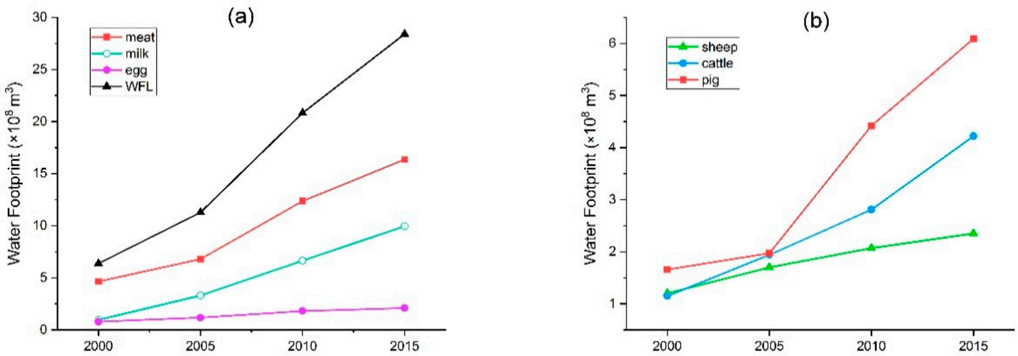

Figure 5. Water footprint changes of (**a**) major livestock products (WFL) and (**b**) meat products.

4.2.4. Water Footprint Changes of Energy

With the development of local society and economy, the industrial structure is constantly adjusting, the proportion of primary industry is gradually declining, the proportion of secondary and tertiary industries are increasing year by year, and the consumption of energy is also increasing rapidly. When compared with 2000, the amount of energy consumption in 2005, 2010, and 2015 increased by 2, 5, and 10 times, respectively. Local energy consumption is dominated by coal and there are abundant coal resources in this region. Before 2005, the consumption of coal was basically self-sufficient; after 2005, it mainly relied on external imports; after 2010, the local coal production was far from enough to support its industrial and agricultural production and socio-economic development; and, by 2015, coal consumption has almost depended on external imports entirely.

Figure 6 shows the changes in the water footprint that were caused by local energy consumption. The import of energy relieves the pressure of local energy production to some extent. The water footprint in the figure is negative, which indicates the external water footprint. The secondary energy source that was dominated by electricity and heat is mainly from the conversion of the primary energy dominated by coal. There are many thermal power plants in the local area, and the production of heat and electricity can also lead to a large amount of blue and grey water footprints. Therefore, it is shown as positive in the figure, which is expressed as the internal water footprint. From 2000 to 2015, the external water footprint of primary energy that is based on fossil fuels and the internal water footprint of secondary energy based on electricity and heat were both expanding, while the total water footprint is negative; that is, the water footprint of energy consumption was mainly based on the external water footprint. However, when compared with the water footprint of agriculture and animal husbandry, the water footprint of energy consumption was relatively small.

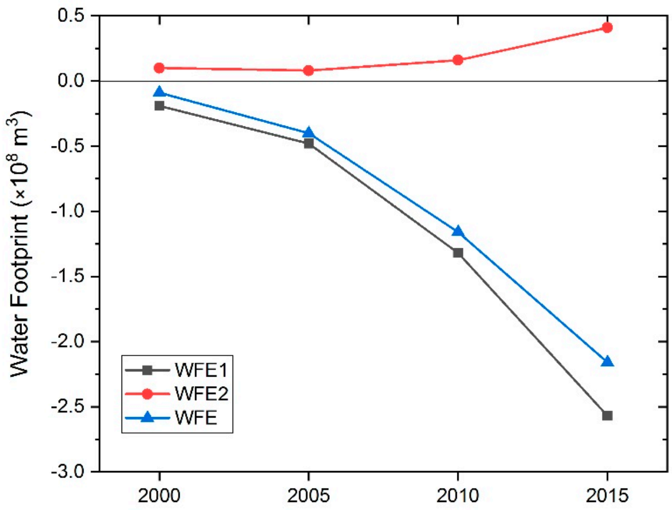

Figure 6. Water footprint changes of main energy consumption from 2000 to 2015, where WFE1 is the water footprint of primary energy, WFE2 is the water footprint of secondary energy, and WFE is the whole water footprint of energy.

In the short term, although the energy consumption has increased rapidly, the whole energy consumption structure of the Manas River Basin has changed little and coal is still the main consumption energy source. On the other hand, the structure of secondary energy has significantly changed. Taking Shihezi City as an example, with the development of electric power resources and the progression of energy technology, the proportion of electricity consumption has shown an obvious upward trend, rising from 6% in 2000 to 16% in 2015, while the thermal energy consumption showed a downward trend year by year, from 14% to 4%, which means that the consumption of thermal power resources was gradually replaced by electric power resources. However, the proportion of secondary energy is not yet too large.

4.3. Risk Assessment of WEF System Based on the Water Footprint in the Basin

The "Water-Energy-Food" risk group is one of the important risk groups for sustainable development issues that are focused on today, while the problems and risks of water in arid areas are more prominent. Water is needed for food production and energy conversion. This paper introduced a water footprint to reflect the risks of the WEF system and tried to evaluate its comprehensive risk.

With the expansion of the production scale and the adjustment of industrial structure, energy consumption has brought about rapid growth of GDP, while also enlarging the multiple risks of the "water-energy-food" system. From 2000 to 2015, agricultural production, water footprint, energy consumption, and GDP increased by 3.1, 2.4, 10.3, and 8.2 times, respectively. Table 4 shows the changes in energy consumption, water footprint, the energy dependence index, and water stress index of the Manas River Basin from 2000 to 2015. With the development of the socio-economy and the expansion of the production scale, local coal resources are gradually being depleted, and the external dependence of energy is rapidly increasing, from being basically self-sufficient in 2000 to almost entirely relying on external imports by 2015.

Table 4. Dynamics of energy dependence and water resource pressure of the basin.

Year	Coal Production	Coal Consumption	Total Water Footprint	Surface Runoff	EDI	WPI
2000	54.61	54.61	17.99	27.22	0.01	0.66
2005	72.77	188.95	23.17	23.41	0.61	0.99
2010	94.51	562.67	30.19	27.65	0.83	1.09
2015	11.55	2012.26	42.38	25.54	0.99	1.66

[1] The units of coal production and coal consumption are 10^4 tce (tons of standard coal equivalent); the units of total water footprint and surface runoff are 10^8 m^3. [2] EDI: Energy dependence index; WPI: Water resources pressure index. [3] The raw coal production and consumption data are from Statistical Yearbook of Shihezi City.

The import of energy means that the virtual water used to produce this part of energy comes from the energy-producing source areas outside the basin, while the energy conversion will produce the internal water footprint locally in this basin. Although the overall energy consumption shows the external water footprint, on the surface, it seems to have reduced the pressure of local water resources, but this effect is very limited. In contrast, the development of industry has driven the development of agriculture, which has led to further expansion of the water footprint. With the expansion of the water footprint, the pressure of water use has also increased gradually from 2000 to 2015. Before 2005, the surface runoff representing renewable surface water resources could basically meet the needs for agricultural production. After 2005, it gradually became overloaded. In operation, it had to rely on the extraction of groundwater to meet the needs of production and living. In fact, when considering industrial water, domestic water, and ecological water, water resources in the basin had already been in an overloaded supply state as early as 2005, and the pressure of water resources should have been greater than estimated.

In addition, it should be noted that the surface water resources that are required for agricultural production depend on the distribution and changes of precipitation. In 2010, due to the abundant rainfall, the water supply pressure of surface runoff was not too large, while in 2015, the precipitation was relatively small, and the distribution was uneven, but the scale of agricultural production had already been too large. The surface runoff was insufficient in supporting agricultural irrigation, leading to a serious water shortage problem, which had to be solved by the overexploitation of groundwater. In 2015, the groundwater exploitation reached 5.4×10^8 m^3, accounting for 45% of the groundwater resources, which placed it in a serious overexploited state.

To further describe on the impact of water overuse and energy overconsumption on the risk of local "water-energy-food" systems in the Manas River Basin, this paper made a more simple linear regression of water footprint and energy consumption (Figure 7a), the water resources pressure index (internal risk) and energy dependence index (external risk) (Figure 7b). R^2 represents the coupling degree between water resource pressure and energy dependence. The two risk indicators have comparatively high positive correlation, which means that the region is more dependent on external energy imports. Meanwhile, the pressure of local water resources is also increasing, thus the whole system is facing both internal and external risks.

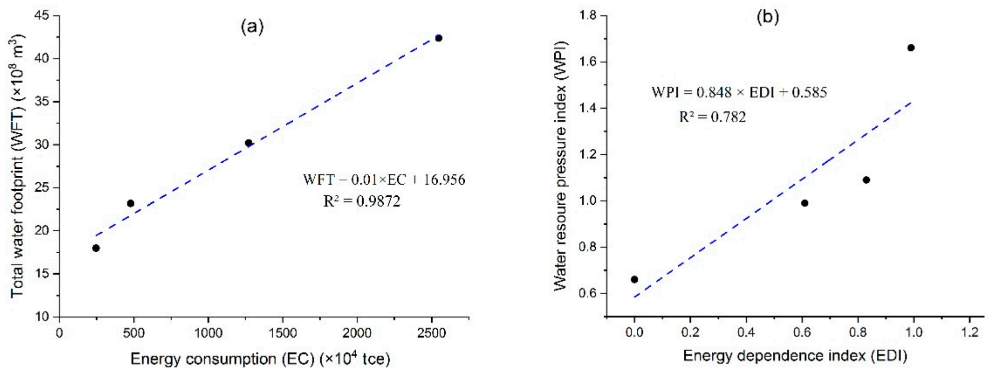

Figure 7. (**a**) Water-energy coupling degree and (**b**) internal-external risk coupling degree of the water, energy, and food (WEF) system in the Manas River Basin.

5. Discussion

5.1. Tradeoffs and Synergies of the Water-Energy-Food Nexus

The development of the socio-economy cannot work without the support of the "water-energy-food" system. There are also interdependent and mutual restriction relationships between these three important strategic resources. Economic development requires energy resources and industrial and agricultural production activities, all of which depend on water [49]. Water resources trade-off between energy and food. In terms of these two resources, the conversion, consumption, and transportation processes are traded off, which will lead to conflicts for sustainable development in the future. The water-energy-food nexus are intertwined and intricate, revealing that the interaction mechanism and optimizing the synergistic interactions have important scientific significance [50–55].

Taking the Manas River Basin as an example, agriculture has always been an important basic industry and it is also a major sector of water resource consumption. After 2000, due to restrictions of land resources and water resources, the space for agricultural development has become increasingly limited and new economic growth points must be found. Therefore, the industrial structure of this basin had been adjusted from 2004 to 2005, and investment and construction in the secondary industry had been increased. Since then, economic development has begun to make rapid progress. Figure 8 shows the changes in GDP and industrial structure in the Manas River Basin. From 2000 to 2015, the local GDP grew rapidly and the proportion of primary industry declined continuously, while the proportion of secondary industry continued to rise. In 2010, the GDP of the secondary industry exceeded that of the primary industry for the first time and then gradually became the leading industry of local economic development.

However, the decline in the GDP proportion of the primary industry does not mean the reduction of the actual scale of the primary industry. In contrast, due to the coupling relationship between the local secondary industry and primary industry, the scale of the primary industry also expanded with the increase of the production capacity of the industrial enterprises. The expanding scale of the primary industry stimulated the development of the secondary industry, because, with the continuous expansion of the scale of planting and breeding, more chemical fertilizers, pesticides, mulch, pipelines, fodders, and machinery and equipment needed to be produced and provided by factories. In fact, although water-saving technologies such as drip irrigation have been widely adopted in the basin, the utilization rate of water resources has been improved, and the virtual water content of agricultural products has been reduced. However, due to the coupling between industries, the rapid development of secondary industry will lead to the expansion of the scale of primary industry to some extent, which will lead to the expansion of the water footprint of primary industry.

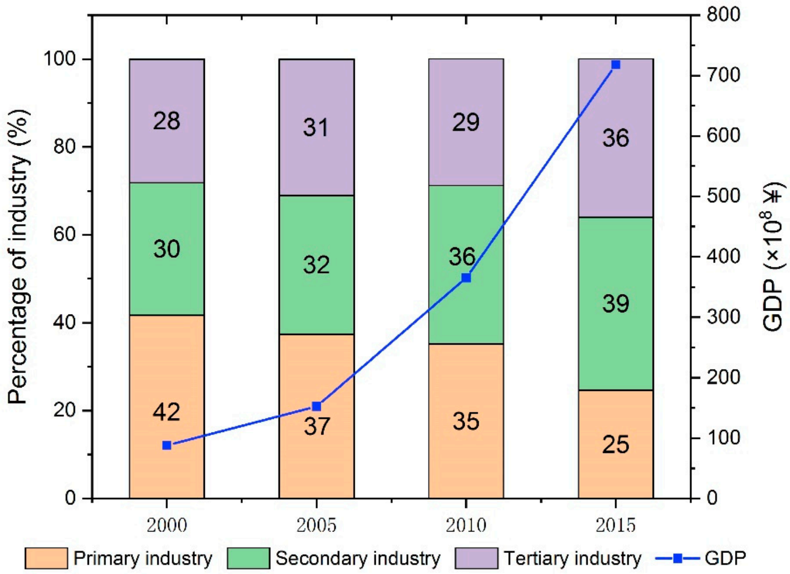

Figure 8. Changes in GDP and industrial structure in the Manas River Basin.

On the other hand, energy has become the main driving force of economic growth. Taking Shihezi City as an example, some of the studies have shown that, before 2004, the energy consumption of Shihezi steadily increased at an annual rate of 6.75%, and after 2005, energy consumption rapidly increased at an annual rate of 25%, which has become the main driving force of economic growth [56]. The traditional economic development mode of "government-led and investment-driven", which is characterized by high energy consumption, not only promotes the rapid growth of GDP but also brings great pressure on local resource supplies, environmental carrying capacity, energy saving, and emission reduction.

Of course, this does not necessarily mean that the greater the consumption of energy leads to a greater pressure on water resource; the coupling of the two is conditional, and both have trade-offs and synergies. There are two ways to solve the energy and water crisis, either decoupling or adjusting, or changing the coupling relationship between them. For example, developing new energy sources, such as hydropower and wind power, will not bring much water consumption. Rather, it can not only reduce the external energy dependence, but also allocate the space-time distribution of surface water resources, which is conducive to the sustainable development of the basin.

5.2. Risk Transfer Chains of the Water-Energy-Food System

The World Economic Forum issued the Global Risk Report (2011) In January 2011. For the first time, the "Water-Energy-Food Nexus" risk group was regarded as one of the three major risk groups in that year. It emphasized that the policy of optimizing a single resource would lead to unpredictable consequences. The overall production and consumption of regional WEF should be taken as a whole, and the relationship between the WEF nexus should be emphasized to ensure the security of the WEF system in the region [10]. There is a clear conductivity between water, energy, and food safety, and the deterioration of one factor will cause a series of chain reactions among them. For example, food production needs to extract groundwater and energy consumption, and a decline in groundwater levels will lead to changes in regional climate, which will, in turn, affect food production [57,58].

In this study area, the basin is faced with the dual risks of external energy dependence and internal water shortage. The fluctuationx of international and domestic energy market prices and climate change that are caused by energy emissions may lead to a series of chain reactions. Figure 9 shows a series of possible impacts on a basin or region that are caused by the transmission of such risks. Some studies have shown that the annual average temperature and annual precipitation in this region fluctuate upward, which may be related to global warming, making the climate of this region warmer and more humid [59,60]. However, it cannot be ignored that, as the temperature rises, the local snow line is also receding, and the thickness of the glacial snow is also decreasing. Glacial snow melting water is one of the main sources of local surface runoff, accounting for more than 30% of the annual runoff [61]. The reduction of glacial snow will obviously threaten the stability of the runoff in the basin. On the other hand, with the increase of precipitation, the precipitation variability and uncertainty also increase. The fragile ecosystems are facing the risk of multiple disasters, which may lead to larger damages and losses and threaten the safety of the entire basin production system and ecosystem.

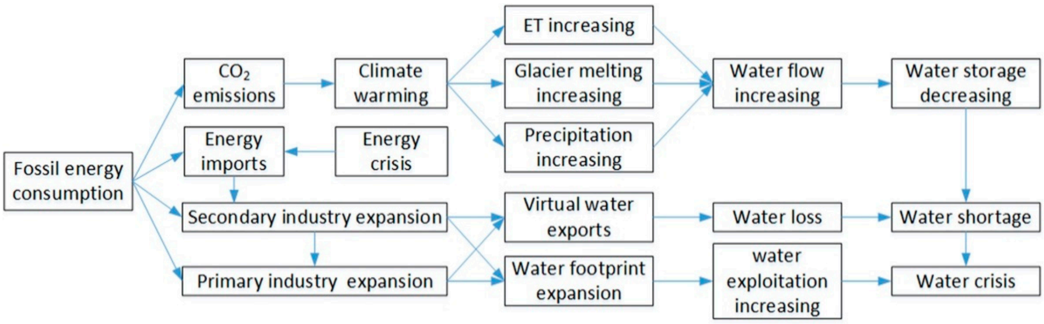

Figure 9. Impact of the energy market and climate fluctuations on the WEF system and risk transfer chains in the basin.

WEF is linked together through the water footprint, which intuitively reflects the direct and indirect driving forces of agricultural production and energy consumption on the expansion of the water footprint, as well as the process of external risk transmission inward and mutual incentives and superpositions with internal risk. While in general, WEF is a complex multivariate system that involves a wide range of aspects. It needs to consider more factors, larger scales, more systematic models and theories, and more detailed research. In this study, the water footprint of energy is only a part of the secondary industrial water footprint. The textile industry and the food processing industry are also water-consuming production sectors, which should be further considered in future research. The analysis, assessment, and prediction of risks also need to be further studied and discussed. Finally, the ultimate goal of this study was to make policy recommendations more scientific, reasonable, and effective, in order to avoid the occurrence of greater risks, and to maintain the sustainable development of the region.

6. Conclusions

Agriculture (including planting and animal husbandry) is the basic industry and the major water user in arid areas, while industrial industry is the leading industry and the major energy consumer in this region. This study showed that the water footprint of agricultural is a much higher than the water footprint of energy consumption. From the perspective of water footprint type, the water footprint of the basin is dominated by the blue water footprint, which accounts for more than 50% of the total water footprint. The green water footprint varies due to annual precipitation changes, while the grey water footprint generally increases, reaching approximately 30% of the total water footprint.

From 2000 to 2015, with the development of the productivity and the adjustment of industrial structure, especially after 2005, energy consumption has brought about rapid GDP growth while also expanding the local water footprint. By 2015, there has been a relatively serious water resource deficit. Thus, the WEF nexus is very significant in this basin. The traditional way of energy consumption and the ever-expanding water resource deficit make the risks transmitted, stimulated, and magnified among the industries within the system, which can be easily affected by fluctuations in energy markets and climate changes, causing operation disorder or even downtime of the system.

Therefore, it is necessary to adjust the industrial structure through macroeconomic regulation and control, and at the same time eliminate outdated production capacity, accelerate the construction and development of new energy, such as wind power, hydropower, and solar power, develop various industries, reduce the coupling degree and system risks, and realize social and economic development transformation through structural reform on the supply side.

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