Water-Saving Potential of Renewable Energy Hydrogen Production in the Yellow River Basin from a Water Footprint Perspective: Postprint

Authors: Li Hui, Yao Xilong

Date: 2025-09-01T11:34:33+00:00

Abstract

Scientifically quantifying and analyzing the water footprint of renewable energy-based hydrogen production and its water-saving potential is of great significance for the high-quality development of the hydrogen energy industry and sustainable utilization of water resources in the provinces (autonomous regions) of the Yellow River Basin. Based on life cycle theory, a bottom-up water footprint evaluation model for hydrogen production technologies is constructed to analyze and compare the water footprints and their composition between renewable energy-based hydrogen production and coal-based hydrogen production. Focusing on the provinces (autonomous regions) of the Yellow River Basin, this study investigates the water-saving intensity of renewable energy-based hydrogen production under different scenarios, while simultaneously exploring the water-saving potential of replacing coal-based hydrogen production with renewable energy-based hydrogen production in each province (autonomous region) by combining differences in electricity mix and water scarcity footprints, using the available water remaining indicator. The results show that: (1) The water scarcity footprint of renewable energy-based hydrogen production is largest in the northern region of the Yellow River Basin, particularly in the northwestern region, with Inner Mongolia having the largest water scarcity footprints for photovoltaic hydrogen production and wind power hydrogen production, at 1167.7$×106*m3and*637.73×$106 m3, respectively. (2) The water-saving intensity of renewable energy-based hydrogen production exhibits a characteristic of "high in the southwest and low in the northeast," with the average water-saving intensity of photovoltaic hydrogen production replacing coal-based hydrogen production and wind power hydrogen production replacing coal-based hydrogen production being 1.04 L · kg-1 and 31.29 L · kg-1, respectively. (3) Inner Mongolia has the greatest water-saving potential for wind power hydrogen production, followed by Qinghai, Gansu, and Shanxi. Qinghai has the greatest water-saving potential for photovoltaic hydrogen production, followed by Gansu and Sichuan. The research findings not only lay a solid foundation for improving water resource utilization efficiency in the Yellow River Basin, but also provide important guidance for the scientific planning and layout of the hydrogen energy industry in the provinces (autonomous regions) of the Yellow River Basin.

Full Text

Water-saving Potential of Hydrogen Production from Renewable Energy in the Yellow River Basin from the Perspective of Water Footprint

LI Hui[1], **YAO Xilong**[2]
[1] School of Economics and Management, Taiyuan University of Science and Technology, Taiyuan 030024, Shanxi, China
[2] College of Economics and Management, Taiyuan University of Technology, Taiyuan 030024, Shanxi, China

Abstract: Scientific quantification and analysis of the water footprint and water-saving potential of renewable energy-based hydrogen production are crucial for the high-quality development of the hydrogen energy industry and sustainable water resource utilization in the provinces (autonomous regions) along the Yellow River. Based on life cycle theory, this study constructs a "bottom-up" water footprint evaluation model for hydrogen production technologies to analyze and compare the water footprints and their compositions between renewable energy-based hydrogen production and coal-based hydrogen production. Focusing on the provinces (autonomous regions) in the Yellow River Basin, we examine the water-saving intensity of renewable energy-based hydrogen production under different scenarios. Additionally, considering provincial differences in power structure and water scarcity footprints, we utilize the Available Water Remaining (AWARE) indicator to investigate the water-saving potential of replacing coal-based hydrogen production with renewable energy-based hydrogen production in each province. The results show that: (1) The water scarcity footprint of renewable energy-based hydrogen production is largest in the northern Yellow River Basin, particularly in the northwestern region. Inner Mongolia exhibits the highest water scarcity footprints for photovoltaic and wind power-based hydrogen production, at 1167.7$×10^{6}$ m^3 and 637.73$×10^{6}$ m^3, respectively. (2) The water-saving intensity of renewable energy-based hydrogen production demonstrates a characteristic of "high in the southwest, low in the northeast." The average water-saving intensities for photovoltaic-based and wind power-based hydrogen production replacing coal-based hydrogen production are 1.04 L · kg^{-1} and 31.29 L · kg^{-1}, respectively. (3) Inner Mongolia shows the greatest water-saving potential for wind power-based hydrogen production, followed by Qinghai, Gansu, and Shanxi. Qinghai demonstrates the highest water-saving potential for photovoltaic-based hydrogen production, followed by Gansu and Sichuan. These findings not only establish a foundation for improving water resource utilization efficiency in the Yellow River Basin but

also provide important guidance for the scientific planning and layout of the hydrogen energy industry in each province (autonomous region) along the Yellow River.

Keywords: renewable energy; hydrogen energy; water footprint; water-saving potential; Yellow River Basin

1. Introduction

Energy and water resources are the material foundation and strategic resources for sustainable economic and social development, representing the most fundamental support for humanity's journey toward sustainable development. Under the "dual carbon" goals, hydrogen energy plays a pivotal role in constructing a new energy system. It not only facilitates deep decarbonization in transportation, industry, and construction sectors but also couples with wind and photovoltaic power generation to promote renewable energy utilization and consumption. China is accelerating the deployment of its hydrogen energy industry. Among existing hydrogen production technologies, renewable energy-based water electrolysis demonstrates the highest water use efficiency. The Yellow River Basin is one of China's most important hydrogen production regions, with the majority of its coal-based hydrogen production enterprises concentrated in the nine provinces (autonomous regions) along the Yellow River. Most hydrogen production facilities are located in areas experiencing water stress or extreme water scarcity, where water supply-demand contradictions are prominent. Against the backdrop of decreasing total water resources and continuously rising water demand from the hydrogen energy industry's rapid development, water shortage remains a severe challenge in the Yellow River Basin. How to scientifically evaluate water resource utilization in the Yellow River Basin's hydrogen energy industry and improve water use efficiency is key to promoting high-quality development of the hydrogen industry.

The water footprint concept, first proposed by Hoekstra based on virtual water theory, measures the volume of water resources consumed in producing a product or service over a certain period. Water footprint links physical and virtual water, identifying both direct and indirect water use by consumers or producers. This concept effectively broadens the theoretical connotation of water resources research and has become an important indicator for water scarcity and water resource impacts. Previous studies have applied water footprint theory to examine water resource consumption, water-energy nexus relationships, and spatial water transfer during energy product production and consumption. For instance, Yan et al. conducted a water footprint quantification assessment of Xinjiang's power industry, analyzing water footprint contribution pathways across different power generation technologies to provide a basis for water footprint accounting in other sectors. Shi et al. established a water footprint evaluation framework for electrolytic hydrogen production, comparing water footprints between grid electricity and renewable energy-based hydrogen production and investigating influencing factors. Current indicators for energy product water footprints mainly include water-saving intensity, water-saving potential, and water scarcity footprint. Water-saving intensity and potential measure water savings from technological improvements or substitutions, while water scarcity footprint quantifies resource consumption trajectories and ecological pressures resulting from water supply-demand imbalances in specific regions or populations.

Existing literature provides a rich foundation for analyzing energy product water footprints, yet several gaps remain: (1) Compared to water footprint studies in other industrial sectors, research on the hydrogen production industry's water footprint is relatively limited, with some studies only analyzing water footprints during hydrogen production rather than the entire life cycle. (2) Few studies examine the impact of hydrogen production technology substitution on water resources at the regional level, particularly in the Yellow River Basin where hydrogen output is high but water supply-demand contradictions are acute. (3) The influence of inter-provincial differences in power structure on water-saving intensity and potential of hydrogen production technologies has not been fully considered, and quantitative research on water-saving potential of renewable energy-based hydrogen production is lacking. Therefore, this study constructs a "bottom-up" water footprint evaluation model for hydrogen production technologies based on life cycle theory, considering both direct water use in hydrogen production and indirect water use from upstream raw materials. The model analyzes water footprints and their compositions across different hydrogen production technologies. Focusing on provinces (autonomous regions) in the Yellow River Basin and considering variations in provincial power structures and remaining available water, this study examines water-saving intensity and potential resulting from hydrogen production technology substitution, providing references for coordinated development between the hydrogen industry and water resources in the Yellow River Basin.

1.1 Study Area Overview

The Yellow River Basin is a crucial energy and basic industrial base in China, playing a significant role in ensuring energy supply security and promoting economic development. The Yellow River stretches 5,464 km with a total area covering nine provinces (autonomous regions): Sichuan, Qinghai, Ningxia, Inner Mongolia, Gansu, Shaanxi, Shanxi, Henan, and Shandong. The Yellow River Basin is a typical resource-scarce watershed, with most areas located in arid and semi-arid regions. Total water resources account for less than 3% of the national total, while per capita water availability is only 1,040 m^3, representing 23% of the national average. The annual average water withdrawal in the Yellow River Basin is 6.5$×10^{10}$ m^3, with water consumption at 4.1$×10^{10}$ m^3, accounting for 63% of water withdrawal. Coal-based hydrogen production in the Yellow River Basin consumes 1.04$×10^{10}$ m^3 of water annually, with water consumption representing 65% of water withdrawal. Long-standing water supply-demand contradictions have severely limited economic and social development in the Yellow River Basin. Therefore, studying water-saving potential for renewable energy-based hydrogen production in the Yellow River Basin is crucial for coordinated economic, social, and ecological development.

1.2 Data Sources

This study utilizes water resources data including total water resources, agricultural water use, domestic water use, industrial water use, ecological and environmental water use, and ecological water consumption, obtained from provincial Water Resources Bulletins (2019-2023). Power generation data comes from the China Electric Power Statistical Yearbook (2019-2023). Renewable energy data is sourced from the China Energy Statistical Yearbook (2019-2023) and provincial Statistical Bulletins on National Economic and Social Development. Hydrogen industry data is collected from official provincial government websites, hydrogen industry development plans, and the hydrogen industry big data platform (https://www.chinah2data.com/#/client/home).

1.3.1 Water Footprint Calculation Method

Grounded in life cycle principles, water footprint comprehensively quantifies water resource consumption from human production activities and effectively reflects the nexus between energy and water resources. This study examines coal-based hydrogen production and renewable energy-based water electrolysis hydrogen production, considering both direct water use in hydrogen production and indirect water use from upstream raw materials. The system boundaries for coal-based and renewable energy-based hydrogen production are illustrated in [Figure 1: see original paper] and [Figure 2: see original paper], respectively.

The life cycle water footprint of coal-based hydrogen production is calculated as follows:

$$\mathrm{HWF}_{\mathrm{cth}} = \mathrm{WF}_{\mathrm{cm}} + \mathrm{WF}_{\mathrm{ct}} + \mathrm{WF}_{\mathrm{cg}} + \mathrm{WF}_{\mathrm{es}}$$

where $\mathrm{HWF}_{\mathrm{cth}}$ represents the water footprint of coal-based hydrogen production ($\mathrm{L} \cdot \mathrm{kg}^{-1}$); $\mathrm{WF}_{\mathrm{cm}}$ denotes water use in coal mining and washing; $\mathrm{WF}_{\mathrm{ct}}$ represents water use in coal transportation; $\mathrm{WF}_{\mathrm{cg}}$ is water use in coal gasification hydrogen production; and $\mathrm{WF}_{\mathrm{es}}$ is water use in electricity supply.

The life cycle water consumption intensity of electricity supply is calculated as:

$$\mathrm{WI}_{\mathrm{ele}} = \sum_{n} \mathrm{WI}_{n} \times \frac{\mathrm{PG}_{n}}{\mathrm{PG}_{\mathrm{total}}}$$

where $\mathrm{WI}_{\mathrm{ele}}$ represents the life cycle water consumption intensity of electricity supply in the nine Yellow River Basin provinces ($\mathrm{L} \cdot \mathrm{kWh}^{-1}$); WI_{n} is the water consumption intensity of the nth power generation technology ($\mathrm{L} \cdot \mathrm{kWh}^{-1}$); PG_{n} is the annual electricity generation of the nth technology in a province; $\mathrm{PG}_{\mathrm{total}}$ is the province's total annual electricity generation; and m is the number of power generation technologies. Water consumption intensities for different power generation technologies are detailed in .

The water footprint of renewable energy-based water electrolysis hydrogen production is calculated as:

$$\mathrm{HWF}_{\mathrm{rel}} = \mathrm{WF}_{\mathrm{el}} + \mathrm{WF}_{\mathrm{re}} + \mathrm{WF}_{\mathrm{co}}$$

where $\mathrm{HWF}_{\mathrm{rel}}$ represents the water footprint of renewable energy-based water electrolysis hydrogen production ($\mathrm{L} \cdot \mathrm{kg}^{-1}$); $\mathrm{WF}_{\mathrm{el}}$ denotes water use in the electrolysis process; $\mathrm{WF}_{\mathrm{re}}$ is water use in renewable electricity generation; and $\mathrm{WF}_{\mathrm{co}}$ is cooling water.

1.3.2 Water-saving Potential Evaluation Method

If the water footprint of renewable energy-based water electrolysis hydrogen production is smaller than that of coal-based hydrogen production, the water-saving intensity is positive, indicating water-saving benefits from renewable energy-based hydrogen production. Conversely, a negative water-saving intensity indicates increased water demand from renewable energy-based hydrogen production.

The water-saving intensity of renewable energy-based hydrogen production in province i is calculated as:

$$\mathrm{HWSI}_i = \mathrm{HWF}_{\mathrm{cth},i} - \mathrm{HWF}_{\mathrm{rel}}$$

where HWSI_i represents the water-saving intensity of renewable energy-based hydrogen production in province i ($\mathrm{L} \cdot \mathrm{kg}^{-1}$).

The water-saving potential is calculated as:

$$\mathrm{HWSP}_i = \mathrm{HWSI}_i \times \mathrm{HP}_i$$

where HWSP_i represents the water-saving potential of renewable energy-based hydrogen production in province i (m^3); and HP_i is the planned hydrogen production capacity in province i (kg).

To better reflect how changes in hydrogen production technology affect available water resources in each province (autonomous region), this study introduces the Available Water Remaining (AWARE) indicator. AWARE assesses the absolute quantity of available freshwater in each region, considering human and environmental freshwater demands. The greater the remaining freshwater, the smaller the burden from new or increased freshwater consumption. This indicator quantifies the likelihood of water scarcity from new water consumption and provides comparability of water consumption impacts across regions.

The AWARE characterization factor for province i is calculated as:

$$\mathrm{AWARE\ CF}_i = \frac{\mathrm{AMD}_{\mathrm{ref}}}{\mathrm{AMD}_i}$$

where AMD_i represents the remaining available freshwater per unit area in province i ($\mathrm{m}^3 \cdot \mathrm{m}^{-2}$); $\mathrm{AMD}_{\mathrm{ref}}$ is the reference value for remaining available water per unit area ($m^3 \cdot m^{-2}$); WS_i is the total water supply in province i (m^3); WC_i is water consumption in province i (m^3); HWC_i is human activity water use in province i (m^3); and AM_i is the actual land area of province i (m^2). A larger AMD_i value corresponds to a smaller AWARE CF_i, indicating greater remaining available water per unit area.

This study couples water-saving intensity and potential with the AWARE characterization factor. The water scarcity footprint, adjusted water-saving intensity, and adjusted water-saving potential are calculated as:

$$\mathrm{HWSF}_i = \mathrm{HWF} \times \mathrm{AWARE\ CF}_i$$

$$\mathrm{HWSIA}_i = \mathrm{HWSI}_i \times \mathrm{AWARE\ CF}_i$$

$$\mathrm{HWSPA}_i = \mathrm{HWSP}_i \times \mathrm{AWARE\ CF}_i$$

where $HWSF_i$ represents the water scarcity footprint ($L \cdot (kg\ eq)^{-1}$); $HWSIA_i$ is the adjusted water-saving intensity ($L \cdot (kg\ eq)^{-1}$); and $HWSPA_i$ is the adjusted water-saving potential (m^3).

2.1 Water Footprint of Hydrogen Production Technologies

The water footprints of coal-based hydrogen production across Yellow River Basin provinces are shown in [Figure 3: see original paper]. Before implementing Carbon Capture, Utilization, and Storage (CCUS) technology, the top three provinces with the highest water footprints are Sichuan, Qinghai, and Gansu, with values of 111.32 $L \cdot kg^{-1}$, 104.76 $L \cdot kg^{-1}$, and 82.87 $L \cdot kg^{-1}$, respectively. After implementing CCUS technology, all provinces show increased water footprints. Sichuan, Qinghai, and Gansu see their coal-based hydrogen water footprints increase to 740.40 $L \cdot kg^{-1}$, 715.00 $L \cdot kg^{-1}$, and 41.25 $L \cdot kg^{-1}$, respectively. CCUS technology consumes substantial water resources during carbon capture, utilization, and storage processes. Although CCUS reduces carbon emissions from coal-based hydrogen production, it increases life cycle water consumption. Variations in coal-based hydrogen production water footprints across provinces primarily stem from differences in provincial power structures. For example, Sichuan's electricity mix is dominated by hydropower, followed by coal power, with minimal wind and solar power generation. In contrast, Ningxia's electricity mix is dominated by coal power, followed by wind and solar power, with minimal hydropower. These differences in power structure lead to varying life cycle water consumption intensities of electricity supply, consequently affecting coal-based hydrogen production water footprints.

As shown in [Figure 4: see original paper], the water footprint of renewable energy-based water electrolysis hydrogen production consists primarily of electrolysis process water use, electricity generation water use, and cooling water. Wind power-based and photovoltaic-based hydrogen production have water footprints of 36.40 $L \cdot kg^{-1}$ and 11.00 $L \cdot kg^{-1}$, respectively, showing significant differences in composition. Wind power-based hydrogen production's electricity water use accounts for 30.22% of its water footprint, while photovoltaic-based hydrogen production's electricity water use accounts for 61.89%. Hydropower-based hydrogen production has a water footprint of 715.00 $\mathrm{L \cdot kg^{-1}}$, significantly higher than photovoltaic and wind power-based hydrogen production. Hydropower-based hydrogen production's electricity water use reaches 715.00 $\mathrm{L \cdot kg^{-1}}$, comprising 96.57% of its water footprint.

2.2 Water-saving Intensity of Renewable Energy-based Hydrogen Production

To investigate the impact of hydrogen production technology substitution on water resources in Yellow River Basin provinces, this study designs two scenarios: Scenario 1 involves photovoltaic-based hydrogen production replacing coal-based hydrogen production, and Scenario 2 involves wind power-based hydrogen production replacing coal-based hydrogen production. Hydropower-based hydrogen production is not considered in scenario design due to its significantly higher water footprint compared to other renewable energy-based hydrogen production methods.

The water-saving intensity of renewable energy-based hydrogen production is illustrated in [Figure 5: see original paper]. Under the photovoltaic replacement scenario, water-saving intensity across the nine Yellow River Basin provinces shows a "high in the southwest, low in the northeast" pattern. Sichuan, Qinghai, and Gansu have positive water-saving intensities of 16.22 $\mathrm{L \cdot kg^{-1}}$, 2.92 $\mathrm{L \cdot kg^{-1}}$, and 1.04 $\mathrm{L \cdot kg^{-1}}$, respectively. The remaining provinces show negative water-saving intensities, with Henan, Shanxi, and Shandong at -6.84 $\mathrm{L \cdot kg^{-1}}$, -8.64 $\mathrm{L \cdot kg^{-1}}$, and -8.34 $\mathrm{L \cdot kg^{-1}}$, respectively. This pattern occurs because southwestern regions have high hydropower shares with substantial water consumption. Photovoltaic-based hydrogen production consumes less water than hydropower, generating water-saving benefits when adopted. Conversely, northeastern regions have large coal power shares, and photovoltaic-based hydrogen production has a higher water footprint than coal-based hydrogen production, thus increasing water demand.

Under the wind power replacement scenario, all nine Yellow River Basin provinces show positive water-saving intensities, indicating water-saving benefits from wind power-based hydrogen production. The average water-saving intensity for wind power-based hydrogen production across the nine provinces is 31.29 $\mathrm{L \cdot kg^{-1}}$. Sichuan, Qinghai, and Gansu have the highest water-saving intensities at 33.17 $\mathrm{L \cdot kg^{-1}}$, while Ningxia has the lowest at 20.81 $\mathrm{L \cdot kg^{-1}}$. Therefore, promoting wind power-based hydrogen production technology can effectively reduce water consumption in the hydrogen industry and alleviate the water-energy tension in the Yellow River Basin.

2.3 Water Scarcity Footprint of Renewable Energy-based Hydrogen Production

The water scarcity footprint of renewable energy-based hydrogen production is shown in . The average water scarcity footprints for photovoltaic-based and wind power-based hydrogen production across the nine Yellow River Basin provinces are 80.80$×10ˆ{6}$ m^3 and 147.96$×10ˆ{6}$ m^3, respectively. Inner Mongolia has the largest water scarcity footprints for both photovoltaic-based and wind power-based hydrogen production at 637.73$×10ˆ{6}$ m^3 and 1167.70$×10ˆ{6}$ m^3, respectively. This is followed by Qinghai, Gansu, Shanxi, Shandong, Ningxia, and Henan. Sichuan has the lowest water scarcity footprints for both photovoltaic-based and wind power-based hydrogen production at 0.88$×10ˆ{6}$ m^3 and 0.48$×10ˆ{6}$ m^3, respectively.

2.4 Water-saving Potential Based on AWARE Characterization Factor

Based on provincial AWARE characterization factors, this study adjusts the water-saving intensity of renewable energy-based hydrogen production technologies across provinces, as shown in [Figure 6: see original paper]. Under the photovoltaic replacement scenario, Qinghai shows the highest adjusted water-saving intensity at 381.18 L • (kg eq)$^{-1}$, followed by Sichuan and Gansu at 124.12 L • (kg eq)$^{-1}$ and 10.28 L • (kg eq)$^{-1}$, respectively. Henan and Shandong show lower adjusted water-saving intensities at 11.64 L • (kg eq)$^{-1}$ and 10.28 L • (kg eq)$^{-1}$, respectively. Under the wind power replacement scenario, northwestern Yellow River Basin provinces show higher adjusted water-saving intensities than other regions, with Qinghai, Inner Mongolia, and Gansu having the highest values at 1092.08 L • (kg eq)$^{-1}$, 381.18 L • (kg eq)$^{-1}$, and 124.12 L • (kg eq)$^{-1}$, respectively.

The adjusted water-saving potential is shown in [Figure 7: see original paper]. The average adjusted water-saving potential for photovoltaic-based hydrogen production across the nine provinces is -1665.98$×10ˆ{6}$ m^3. Qinghai, Gansu, and Sichuan show positive potentials of 1525.01$×10ˆ{6}$ m^3, 4368.60$×10ˆ{6}$ m^3, and 90.53$×10ˆ{6}$ m^3, respectively. Inner Mongolia, Shanxi, and Shaanxi show negative potentials of -16119.35$×10ˆ{6}$ m^3, -470.04$×10ˆ{6}$ m^3, and -205.89$×10ˆ{6}$ m^3, respectively. The average adjusted water-saving potential for wind power-based hydrogen production is 5049.20$×10ˆ{6}$ m^3. Inner Mongolia has the largest potential at 36878.42$×10ˆ{6}$ m^3, followed by Qinghai, Gansu, and Shanxi at 4368.60$×10ˆ{6}$ m^3, 2336.23$×10ˆ{6}$ m^3, and 1175.48$×10ˆ{6}$ m^3, respectively.

To better compare differences between adjusted and unadjusted water-saving potentials, this study analyzes typical provinces including Shanxi, Gansu, and Sichuan. As shown in [Figure 8: see original paper], Gansu and Sichuan have photovoltaic-based hydrogen production water-saving potentials of

58.47$×10^{6}$ m^3 and 41.92$×10^{6}$ m^3, respectively. Gansu's potential is 1.39 times that of Sichuan, but due to differences in remaining available water resources, Gansu's adjusted potential is 48.3 times that of Sichuan. Therefore, replacing coal-based hydrogen production with photovoltaic-based hydrogen production in Gansu would generate greater water-saving benefits. Shanxi and Shandong have photovoltaic-based hydrogen production water consumption potentials of 174.54$×10^{6}$ m^3 and 110.87$×10^{6}$ m^3, respectively. Shanxi's potential is 1.57 times that of Shandong, but its adjusted water consumption potential is 4.2 times that of Shandong. Thus, photovoltaic-based hydrogen production substitution would impose more severe water pressure on Shanxi than on Shandong.

As shown in [Figure 9: see original paper], Shandong and Shaanxi have wind power-based hydrogen production water-saving potentials of 663.47$×10^{6}$ m^3 and 198.30$×10^{6}$ m^3, respectively. Shandong's potential is 3.34 times that of Shaanxi, but after accounting for remaining available water resources, Shandong's adjusted potential is 1.5 times that of Shaanxi. Therefore, replacing coal-based hydrogen production with wind power-based hydrogen production would generate greater water-saving benefits in Shaanxi. Gansu and Shanxi have wind power-based hydrogen production water-saving potentials of 291.45$×10^{6}$ m^3 and 436.51$×10^{6}$ m^3, respectively. Shanxi's potential is 1.5 times that of Gansu, but Gansu's adjusted potential is 1.8 times that of Shanxi. Thus, wind power-based hydrogen production substitution would generate greater water-saving benefits in Gansu.

3 Discussion

This study reveals that replacing coal-based hydrogen production with renewable energy-based hydrogen production can effectively conserve water resources and improve water use efficiency in water-scarce regions. The water-saving intensity of renewable energy-based hydrogen production shows a "high in the southwest, low in the northeast" pattern, consistent with previous research findings. Variations in water-saving potential across Yellow River Basin provinces primarily result from two factors: first, differences in provincial power structures lead to varying water footprints for coal-based hydrogen production; second, differences in remaining available water resources across provinces. Taking Qinghai and Sichuan as examples, Qinghai's electricity mix is dominated by hydropower (50.71%), followed by wind and solar power (34.22%), while Sichuan's electricity mix includes 82.21% hydropower and only 14.72% coal power, with wind and solar accounting for just 3.07%. Based on water footprint calculations, coal-based hydrogen production water footprints in Qinghai and Sichuan are 104.76 $\mathrm{L \cdot kg^{-1}}$ and 82.87 $\mathrm{L \cdot kg^{-1}}$, respectively. Additionally, according to provincial water resource utilization and land area, remaining available freshwater per unit area in Qinghai and Sichuan is 0.001 $\mathrm{m^3 \cdot m^{-2}}$ and 0.023 $\mathrm{m^3 \cdot m^{-2}}$, respectively. These factors collectively result in different water-saving potentials for renewable energy-based hydrogen production in Qinghai and Sichuan.

Specifically, Qinghai and Sichuan have photovoltaic-based hydrogen production water-saving potentials of 1525.01$×10^{6}$ m^{3} and 50.47$×10^{6}$ m^{3}, respectively, and wind power-based hydrogen production water-saving potentials of 4368.60$×10^{6}$ m^{3} and 90.53$×10^{6}$ m^{3}, respectively. Furthermore, compared to photovoltaic-based hydrogen production, wind power-based hydrogen production can more effectively reduce water consumption in the hydrogen industry, safeguard water security in the Yellow River Basin, and represents the optimal pathway for sustainable development of the hydrogen energy industry in Yellow River Basin provinces.

Conclusion

To investigate water-saving potential for renewable energy-based water electrolysis hydrogen production in the Yellow River Basin, this study constructs a "bottom-up" water footprint evaluation model for hydrogen production technologies from a life cycle perspective. The model analyzes water footprints and their compositions across different hydrogen production technologies and examines water-saving intensity under various scenarios. Using the Available Water Remaining indicator, the study investigates water-saving potential from replacing coal-based hydrogen production with renewable energy-based hydrogen production in each province. The main conclusions are:

1. Significant differences exist in water footprints and their compositions across hydrogen production technologies. For coal-based hydrogen production, water use during hydrogen production and electricity generation accounts for the largest share of the water footprint. For renewable energy-based hydrogen production, electricity generation water use dominates, followed by cooling water, with electrolysis process water use contributing the smallest share. Moreover, the water scarcity footprint of renewable energy-based hydrogen production is largest in northern Yellow River Basin provinces, particularly in northwestern provinces.

2. Water-saving intensity for renewable energy-based hydrogen production in the Yellow River Basin demonstrates a "high in the southwest, low in the northeast" pattern. The average water-saving intensity for photovoltaic-based hydrogen production across Yellow River Basin provinces is 1.04 $\mathrm{L \cdot kg^{-1}}$, with positive values only in Sichuan, Qinghai, and Gansu. All other provinces show negative values, indicating that photovoltaic-based hydrogen production would increase water demand in these regions. The average water-saving intensity for wind power-based hydrogen production is 31.29 $\mathrm{L \cdot kg^{-1}}$, with all provinces showing positive values, demonstrating that wind power-based hydrogen production substitution can significantly reduce water consumption and alleviate water pressure across all provinces.

3. Inner Mongolia has the greatest water-saving potential for wind power-based hydrogen production, followed by Qinghai, Gansu, and Shanxi.

> Qinghai has the highest water-saving potential for photovoltaic-based hydrogen production, followed by Gansu and Sichuan. Therefore, from the perspectives of efficient water resource utilization and sustainable hydrogen energy industry development, Qinghai and Gansu are suitable for developing both wind power-based and photovoltaic-based hydrogen production, while Inner Mongolia and Shanxi are more suitable for wind power-based hydrogen production.

This study has certain limitations. For instance, the scenario simulation only considers hydrogen production technology substitution without forecasting other development trends. Future scenario simulations should incorporate detailed projections of social, economic, and technological development trends related to hydrogen production to provide scientific foundations for regional water-energy synergy development and hydrogen industry planning.

References

[1] Yan Chenjian, Li Meng, Zhuo La, et al. Spatiotemporal evolution of water footprint and water saving potentials of crop production in Shaanxi Province during 1989—2019[J]. Resources Science, 2023, 45(1): 158-173.

[2] An Hui, Wang Yonghao, An Min, et al. Spatial temporal evolution of water resources green efficiency and potential of water saving and emission abating in cities along Yangtze River economic belt[J]. Resources and Environment in the Yangtze Basin, 2023, 32(4): 692-705.

[3] Wang Zhiqiang, Jiang Wenhuan, Lu Shiyue. Characteristics of water energy carbon coupling system in Xinjiang based on the ecological network analysis[J]. Arid Land Geography, 2023, 46(12): 2005-2016.

[4] Chen Hongbo, Yang Lai. Path selection for China's hydrogen industry development under the goal of carbon neutrality[J]. China Population, Resources and Environment, 2024, 34(10): 94-105.

[5] Zhang Xian, Xu Mao, Xu Dong, et al. Carbon footprint assessment of coal hydrogen technology combined with CCUS in China[J]. China Population, Resources and Environment, 2021, 31(12): 1-11.

[6] Jiang Kejuan, Feng Shengbo. Going to the mitigation targets in Paris Agreement: The world is on the road[J]. Climate Change Research, 2021, 17(1): 1-6.

[7] Irena B. Water for hydrogen production[R]. United Arab Emirates: International Renewable Energy Agency, Bluerisk, 2023.

[8] Yang Yanyan, Wang Yongyu, Xu Qiyang. Driving factors and decoupling effect of water resources utilization in the Yellow River Basin[J]. Arid Land Geography, 2025, 48(1): 20-30.

[9] Hoekstra A Y, Huang P O. Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade[J]. Water

Science & Technology, 2002, 49(11): 203-209.

[10] Yan Shuqi, Li Sumei, Lü He, et al. Water footprint analysis of electricity production in Xinjiang Uygur Autonomous Region based on a hybrid LCA model and its changes under carbon neutralization target[J]. Climate Change Research, 2022, 18(3): 294-304.

[11] Shi X P, Liao X, Li Y F. Quantification of fresh water consumption and scarcity footprints of hydrogen from water electrolysis: A methodology framework[J]. Renewable Energy, 2020, 154: 786-796.

[12] Liao X W, Zhao X, Liu W F, et al. Comparing water footprint and water scarcity footprint of energy demand in China's six megacities[J]. Applied Energy, 2020, 269: 115137, doi: 10.1016/j.apenergy.2020.115137.

[13] Li J J, Yan Y L, Wang Y R, et al. Spatial successive transfer of virtual scarcity water along China's coal based electric chain[J]. Energy, 2024, 288: 129678, doi: 10.1016/j.energy.2023.129678.

[14] Tian Jiaxin, Dang Xiaohu, Yang Zhi, et al. Analysis of water security risk of cash forest expansion in the Loess Plateau in terms of water footprint: A case study of apple planting[J]. Journal of Natural Resources, 2022, 37(10): 2750-2762.

[15] Gao Yamiao, Chen Haonan, Wang Fang, et al. Spatio temporal evolution of water footprint of typical grain crops and evaluation of water saving potential in Ningxia[J]. Arid Land Geography, 2024, 47(12): 2005-2016.

[16] Fang Delin, Song Changqing, Li Chenghang, et al. Analysis of water stress and driving factors based on virtual water flows in China[J]. Acta Geographica Sinica, 2025, 80(3): 712-723.

[17] Zhao Yong, Huang Kejing, Gao Xuerui, et al. Evaluation of grain production water footprint and influence of grain virtual water flow in the Yellow River Basin[J]. Water Resources Protection, 2022, 38(4): 39-47.

[18] Zhu Yongnan, Wang Jianhua, Liu He, et al. Analysis of spatial and temporal evolution of water footprint of interregional and inter provincial electricity trading in northwest China[J]. Water Resources and Power, 2021, 39(11): 69-71, 162.

[19] Henriksen M S, Matthews H S, White J, et al. Tradeoffs in life cycle water use and greenhouse gas emissions of hydrogen production pathways[J]. International Journal of Hydrogen Energy, 2024, 49: 1221-1234.

[20] Guan Wei, Zhao Xiangning, Xu Shuting. Spatiotemporal feature of the water footprint of energy and its relationship with water resources in China[J]. Resources Science, 2019, 41(11): 2008-2019.

[21] Yang Q, Huang T Y, Chen F Y, et al. Water saving potential for large scale photovoltaic power generation in China: Based on life cycle assess-

ment[J]. Renewable and Sustainable Energy Reviews, 2022, 167: 112681, doi: 10.1016/j.rser.2022.112681.

[22] Shi X P, Liao X, Li Y F. Quantification of fresh water consumption and scarcity footprints of hydrogen from water electrolysis: A methodology framework[J]. Renewable Energy, 2020, 154: 786-796.

[23] Ma C, Liu W W, Gou H X, et al. Water conservation potential of energy intensive industries under clean energy and electricity substitution: A case study of nine provinces along the Yellow River Basin[J]. Journal of Environmental Management, 2024, 371: 123256, doi: 10.1016/j.jenvman.2024.123256.

[24] Du L F, Yang Y M, Bai X, et al. Water scarcity footprint and water saving potential for large scale green hydrogen generation: Evidence from coal hydrogen substitution in China[J]. Science of the Total Environment, 2024, 940: 173589, doi: 10.1016/j.scitotenv.2024.173589.

[25] Li G, Ma S Q, Liu F, et al. Life cycle water footprint assessment of syngas production from biomass chemical looping gasification[J]. Bioresource Technology, 2021, 342: 125940, doi: 10.1016/j.biortech.2021.125940.

[26] Cui P Z, Xu Z F, Yao D, et al. Life cycle water footprint and carbon footprint analysis of municipal sludge plasma gasification process[J]. Energy, 2022, 261: 125280, doi: 10.1016/j.energy.2022.125280.

[27] Pfister S, Scherer L, Buxmann K. Water scarcity footprint of hydropower based on a seasonal approach: Global assessment with sensitivities of model assumptions tested on specific cases[J]. Science of the Total Environment, 2020, 724: 138188, doi: 10.1016/j.scitotenv.2020.138188.

[28] Chen Q Y, An T L, Lu S B, et al. The water footprint of coal fired electricity production and the virtual water flows associated with coal and electricity transportation in China[J]. Energy Procedia, 2019, 158: 3519-3527.

[29] Hou Linxiu, Wen Lu, Zhao Ji, et al. Evaluation of water resource utilization in Alxa League based on water footprint method[J]. Journal of Arid Land Resources and Environment, 2020, 34(12): 35-41.

[30] Lu Zhonggui, Kang Zhe, Li Wei, et al. Water scarcity assessment in the Yellow River Basin from comprehensive perspective of water quantity water quality ecology water demand[J]. Water Resources Protection, 2024, 40(4): 73-81.

[31] Du Yaming, Bai Yongping, Liang Jianshe, et al. Comprehensive measurement and influencing factors of carbon emission efficiency of tourism in the Yellow River Basin[J]. Arid Land Geography, 2023, 46(12): 2074-2085.

[32] Zhang Haoran, Xu Kangning, Guo Fei, et al. Research on the sustainable utilization of water resources in the Yellow River Basin based on water resources ecological footprint[J]. Journal of Environmental Engineering Technology, 2024, 14(6): 1732-1742.

[33] Yang Zhouyi, Xing Haijun, Jiang Jianwei, et al. Optimal scheduling of integrated energy system with coal hydrogen and carbon-capture power plant based on low carbon demand response[J]. Electric Power Automation Equipment, 2024, 44(4): 25-32.

[34] Wang Zhiqiang, Jiang Wenhuan, Lu Shiyue. Characteristics of water energy carbon coupling system in Xinjiang based on the ecological network analysis[J]. Arid Land Geography, 2023, 46(12): 2005-2016.

Note: Figure translations are in progress. See original paper for figures.