Constructing Unit-based Multi-energy Complementary Energy Bases to Facilitate Clean Development in the Yellow River Basin

Authors: Zhang Yuansheng, Lian Jijian, Zhang Jinliang, Xing Jianying, Jinliang Zhang

Date: 2020-07-05T00:00:00+00:00

Abstract

This paper proposes a unit-based clean energy construction model based on multi-energy complementarity of wind, solar, hydroelectric, and pumped-storage, which integrates the Heishanxia, Qikou, and Guxian hydraulic hub projects planned under the Yellow River water-sediment regulation system, relies on the abundant water, wind, solar, land, and topographic resources in the 'Ji' character bend region of the Yellow River, achieves stable output through power source-side regulation, and puts forward the concept of constructing three clean energy bases featuring wind-solar-hydro-pumped-storage multi-energy complementarity to replace fossil energy, realize water conservation and emission reduction, and facilitate ecological protection and high-quality development of the Yellow River Basin.

Full Text

Building Unitary Multi-Energy Complementary Energy Bases to Promote Clean Development in the Yellow River Basin

ZHANG Yuan-sheng[1], **LIAN Ji-jian**[1], **ZHANG Jin-liang**[2], **XING Jian-ying**[2]

(1. State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China;
2. Yellow River Engineering Consulting Co. Ltd., Zhengzhou 450003, China)

Abstract This paper proposes a unitary clean energy construction model based on multi-energy complementarity of wind, solar, hydropower, and pumped-storage energy storage. Combined with the Heishanxia, Qikou, and Guxian water conservancy projects planned under the Yellow River water-sediment regulation system, and leveraging the abundant water, wind, solar, land, and terrain resources in the Yellow River's Ω-shaped bend region, this model achieves stable output through power-source-side regulation. The paper presents a concept for constructing three wind-solar-hydro-pumped-storage multi-energy complementary clean energy bases to replace fossil energy, realize water conservation and emission reduction, and support ecological protection and high-quality development in the Yellow River Basin.

[**Keywords**] Ω-shaped bend region; high-quality development; multi-energy complementarity; energy base

The Yellow River Basin serves as China's "energy river basin," rich in coal, oil, and natural gas resources, with coal reserves accounting for over half of the national total. Among the 14 planned coal power bases nationwide, 10 are distributed in the Yellow River Basin. Large-scale coal power development not only consumes enormous water resources but also generates substantial emissions of greenhouse gases and pollutants such as carbon dioxide and sulfur dioxide. In May 2020, the "Guidelines on Promoting Western Development to Form a New Pattern in the New Era" issued by the Central Committee of the Communist Party of China and the State Council proposed "strengthening renewable energy development and utilization, launching research on large-scale energy storage projects at Yellow River cascade hydropower stations, and cultivating clean energy bases; accelerating local consumption of wind and photovoltaic power generation." This 指明了 the direction for clean energy development and utilization in China's western regions, particularly the Yellow River Basin.

The Yellow River's Ω-shaped bend region refers to the area encircled by the Ω-shaped bend formed as the Yellow River flows through Gansu, Ningxia, Inner Mongolia, Shaanxi, and Shanxi provinces [1]. This region represents a crucial energy production area in the Yellow River Basin and across the nation. However, because most of its energy output consists of fossil fuels [2], it has long faced ecological and environmental challenges including high water consumption, severe pollution, and substantial emissions. Focusing on the major national strategy of ecological protection and high-quality development in the Yellow River Basin, and following the "Guidelines on Promoting Western Development," this paper analyzes current energy development issues and trends based on energy development needs and impacts. It proposes a unitary clean energy construction concept based on wind-solar-hydro-pumped-storage multi-energy complementarity to build three clean energy bases in the Yellow River's Ω-shaped bend region, thereby supporting high-quality development in the basin.

1.1 Current Energy Structure in the Yellow River' s Ω-Shaped Bend Region

China' s resource endowment features abundant coal, limited oil, and scarce natural gas [3], resulting in a current energy mix dominated by fossil fuels. Data show that fossil energy accounted for 84.7% of total energy consumption in 2019 [4], representing a resource-depleting and environmentally polluting energy supply model that not only contradicts sustainable development principles but also severely impedes ecological quality improvement, falling short of the vision for a Beautiful China with perpetual green mountains, clear waters, and fresh air. This characteristic is particularly pronounced in the Yellow River' s Ω-shaped bend region [5].

According to energy production and consumption data for provinces in the Ω-shaped bend region (see Table -1), total energy production in these provinces reached 1,830.58 million tons of standard coal equivalent in 2018, representing approximately 51% of national energy production. Energy production in the region relies primarily on fossil fuels such as raw coal and crude oil, with fossil energy production exceeding 90% in Ningxia, Inner Mongolia, and Shanxi. Regarding the balance between production and consumption, all provinces except Gansu and Ningxia produce more energy than they consume, meaning the main provinces in the Ω-shaped bend region supply energy to other regions beyond meeting local demand.

Table 1-1 Energy Production and Consumption in Provinces of the Yellow River' s Ω-Shaped Bend Region (10,000 tons of standard coal equivalent)

Note: (1) Data sourced from provincial statistical yearbooks for 2018. (2) In 2017, Ordos City, located in the Ω-shaped bend region, accounted for approximately 66.5% of Inner Mongolia' s raw coal production and 100% of its natural gas production.

1.2 Challenges Facing the Ω-Shaped Bend Region

The Ω-shaped bend region represents the most geographically distinctive area of the Yellow River Basin and holds a pivotal position in western development strategy. With similar resource endowments and converging industrial structures, the region faces several development challenges:

(1) **Insufficient comprehensive resource utilization**. As an energy-rich region, the Ω-shaped bend area has developed multiple energy sources including coal, oil and gas, coal-to-gas, electricity, refined oil, wind power, and photovoltaic generation. However, fossil energy consumption remains dominant overall, water resources are relatively scarce, and wind and solar curtailment is widespread [6]. Multiple energy sources have not formed synergistic strength, indicating a need to enhance comprehensive and circular resource utilization.

(2) **Underutilized power transmission potential**. The region' s local

electricity demand is limited, and the transmission capacity of northwest power grid outbound channels is constrained by dispatch mechanisms and renewable generation forecasting accuracy. Regional peak-shaving capacity requires improvement, and transmission potential remains insufficiently exploited [7].

(3) **Fragile ecological environment**. The Ω-shaped bend region constitutes a vital component of the Yellow River' s "three zones and one corridor" ecological corridor, encompassing mostly arid and semi-arid areas with scarce precipitation. It also serves as a major source of Yellow River sediment [8], representing a typical ecologically vulnerable zone. Natural disasters including high temperatures, drought, strong winds, and sandstorms, combined with increasing desertification and soil erosion, have created a fragile ecological environment. Ecologically friendly energy development has become imperative.

(4) **Prominent environmental pollution issues**. As a crucial national energy and chemical industry base, the region exhibits obvious resource-based industrial characteristics. Long-term large-scale development has exerted tremendous pressure on the already fragile local ecosystem, causing varying degrees of pollution to atmospheric, water, and soil environments [9]. Developing new clean energy represents the future development trend.

2 Energy Development Trends in the Yellow River' s Ω-Shaped Bend Region

The national strategy for ecological protection and high-quality development in the Yellow River Basin, coupled with the new pattern of western development in the new era, has established new requirements for energy development in the Ω-shaped bend region. The energy supply structure will continue optimizing, with building a clean, low-carbon, safe, and efficient modern energy system representing a major historical mission for energy development reform. To achieve China' s carbon emission peak target around 2030 and implement the Yellow River Basin ecological protection and high-quality development strategy for creating an ecological civilization society, clean energy will maintain rapid growth. The region' s hydropower resources have a technically developable capacity of 25,352.5 MW and an economically developable capacity of 23,510.1 MW [10]. Inner Mongolia within the region belongs to Class II wind resource areas with abundant wind energy; areas flowing through Gansu and Ningxia belong to Class III wind resource areas with relatively rich wind energy; Shaanxi and Shanxi belong to Class IV wind resource areas with certain development value. Regarding solar resources, northern Ningxia belongs to Class I solar resource areas with annual radiation totals of 6,680-8,400 MJ/m^2 and annual sunshine hours of 3,200-3,300 hours; central Gansu and southern Inner Mongolia belong to Class II solar resource areas with annual radiation totals of 5,852-6,680 MJ/m^2 and annual sunshine hours of 3,000-3,200 hours; Shaanxi and Shanxi contain

Class II, III, and IV areas from south to north with annual radiation totals of 4,180-5,016 MJ/m^2 and annual sunshine hours of 3,000-2,000 hours. These data indicate that hydropower resources remain underdeveloped and wind-solar resources are abundantly available, making clean energy development a continued growth driver for the region [11].

Since the proposal of the major national strategy for Yellow River Basin ecological protection and high-quality development, scholars and institutions have conducted in-depth investigations [12-15]. The consensus recognizes that, based on full consideration of upstream, midstream, and downstream differences, water resources should be used conservatively and intensively to promote ecological protection and high-quality development. As an important energy base, transforming energy development and utilization patterns provides an opportunity for high-quality development. Recent research and preliminary practices in new energy technologies such as multi-energy layered and zoned complementarity and cascade hydropower station energy storage [16-21] have laid a solid foundation.

3 Concept for Multi-Energy Complementary Clean Energy Bases in the Yellow River' s Ω-Shaped Bend Region

Northwest China boasts some of the country' s richest wind and solar resources. However, due to the random and fluctuating nature of wind and solar power generation systems [22], combined with the relatively low load level and insufficient peak-shaving capacity of the northwest power grid and constraints from outbound transmission channels, wind and solar resources have not been fully developed or effectively utilized. Hydropower, as a green and renewable energy source, possesses excellent peak-shaving capability, but this capacity is limited when power generation dispatch is subordinate to water dispatch, particularly when hydropower constitutes a small proportion of the grid. Pumped-storage power stations, as the most scalable and technologically mature energy storage method, can not only enhance grid peak-shaving response capability but also improve grid accommodation capacity for wind and solar power generation.

Based on the water conservancy projects in the Ω-shaped bend region planned in the "Yellow River Basin Comprehensive Plan" [23], combined with the vast desert, sandy land, and loess hilly-gully land resources in northwest China and abundant wind and solar resources, this concept deploys a regional energy cooperation mechanism, implements an innovation-driven development strategy, promotes complementary energy technologies, and creates three major multi-energy complementary clean energy base projects at Heishanxia, Guxian, and Qikou.

3.1 Water Resources The Heishanxia, Qikou, and Guxian water conservancy projects in the Yellow River' s Ω-shaped bend region, along with the existing Longyangxia, Liujiaxia, Sanmenxia, and Xiaolangdi projects, constitute the seven major water-sediment regulation backbone projects proposed in the

2013 State Council-approved "Yellow River Basin Comprehensive Plan" (see Figure [Figure 3: see original paper]-1). In addition to coordinating water-sediment relationships, ice flood prevention, flood control, rational water resource allocation, and water supply, these projects can generate substantial electricity using head differences between upstream and downstream. According to the plan, Heishanxia will have 2 million kW installed capacity, Qikou 1.8 million kW, and Guxian 2.1 million kW.

3.2 Wind, Solar, and Land Resources **Figure 3-1** Schematic diagram of three proposed water conservancy projects in the Yellow River' s Ω-shaped bend region

The Heishanxia reach in Gansu Province' s Baiyin City lies in the hinterland of northern Gansu, on the southern edge of the Tengger Desert, in a transitional zone between the Loess Plateau and the Tengger Desert. The terrain slopes from high in the southwest to low in the northeast, with maximum elevation of 3,321 m and minimum of 1,276 m. Zhongwei City has terrain sloping from high southwest to low northeast, with an average elevation of 1,225 m. Landforms include five types: Yellow River alluvial plains, terraces, deserts, mountains, and hills. Both areas feature typical temperate continental monsoon climates. Influenced by the desert environment, they enjoy abundant sunshine with annual radiation totals of 6,680-8,400 MJ/m^2 and annual sunshine hours of approximately 3,300 hours, belonging to Class I solar resource areas. Wind resources are relatively abundant, belonging to Class III wind resource areas. Preliminary estimates indicate that wind-solar energy bases along both banks of the Yellow River would cover approximately 1,500 km^2 with a planned installed capacity of about 20 million kW.

The Qikou reach in Shaanxi Province' s Yulin City (eastern part) and Shanxi Province' s Lüliang City (western part) possesses conditions for wind-solar resource development and utilization. Yulin' s terrain slopes from west to east, with average elevation of 1,600-1,800 m in the southwest and 1,000-1,200 m elsewhere. It is one of China' s high sunshine value areas, with annual average sunshine hours of 2,593-2,914 hours (highest in the northeast, lowest in the south). Lüliang lies in the middle section of the Lüliang Mountains, with terrain high in the middle and low on both sides. The Lüliang Mountains run north-south through the entire area, with average elevation of 1,000-2,000 m. Landforms include three types: wind-sand grassland areas, loess hilly-gully areas, and low mountain-hill areas, with average sunshine hours of 2,351-2,871 hours. These regions belong to Class III solar resource areas and Class IV wind resource areas, offering certain development value and suitability for large-scale wind-solar projects. Preliminary estimates indicate that wind-solar energy bases along both banks of the Yellow River would cover approximately 2,000 km^2 with a planned installed capacity of about 10 million kW.

The Guxian reach along both banks of the Yellow River includes eastern Yan' an City in Shaanxi, and western Linfen and Yuncheng cities in Shanxi, all possessing conditions for wind-solar resource development and utilization. Yan' an lies in the middle reaches of the Yellow River, within the loess plateau hilly-gully region, dominated by loess plateau and hills sloping from high northwest to low southeast, with average elevation of approximately 1,200 m. It belongs to the warm temperate semi-humid drought-prone climate zone with annual sunshine hours of approximately 2,418 hours. Linfen has annual average sunshine hours of 1,748-2,512 hours. Yuncheng features relatively complex terrain with obvious relative elevation differences. The highest point is Shunwangping in Yuanqu County at 2,321.8 m elevation, while the lowest point is where the Xiyang River enters the Yellow River in Yuanqu County at 180 m elevation. Affected by monsoon activities year-round, it belongs to the warm temperate continental monsoon climate with sunshine duration of approximately 2,039 hours. These three regions contain multiple landform types including plains, mountains, hills, basins, and terraces, belonging to Class III solar resource areas and Class IV wind resource areas, offering certain development value and suitability for large-scale wind-solar projects. Preliminary estimates indicate that wind-solar energy bases along both banks of the Yellow River would cover approximately 1,300 km^2 with a planned installed capacity of about 7 million kW.

3.3 Terrain Resources The Heishanxia reach consists of canyons and flatlands, with a 21 km stretch from the dam site to the canyon inlet. Both banks feature steep mountains with developed gullies and relative elevation differences exceeding 300 m, satisfying conditions for pumped-storage power station construction in terms of both terrain and water source availability. Following pumped-storage power station siting principles and considering regulation cycle requirements, five sites were selected and compared in the Huxia Reservoir and Daliushu Reservoir areas based on criteria including: head difference between upper and lower reservoirs greater than 300 m, distance-to-height ratio not exceeding 8, maximum-to-minimum head ratio less than 1.25, and maximum dam height of upper reservoir not exceeding 150 m. Two sites demonstrated favorable conditions, with a preliminary proposed installed capacity of 3 million kW.

The Qikou Reservoir area lies in the upper section of the Shanxi-Shaanxi Canyon, belonging to a relatively uplifted mountainous plateau region. Within 2 km of the reservoir, the area mostly consists of loess ridges, plateaus, and mounds at elevations of 800-1,000 m. The Yellow River flows north-south through the reservoir area, forming the local lowest erosion base level with relative elevation differences of approximately 200 m. Following pumped-storage siting principles and considering the principle of maximizing the regulation storage capacity, dam sites were selected on both left and right banks of the Qikou Reservoir area, with a preliminary proposed installed capacity of 2.4 million kW.

The Guxian project area lies in the southern section of the Shanxi-Shaanxi Canyon, belonging to a relatively uplifted mountainous plateau region. The Lüliang Mountains lie to the east and the Weibei Mountains to the west. Within 2 km of the reservoir, the area mostly consists of loess ridges, plateaus, and mounds at elevations of 800-1,000 m. The Yellow River flows north-south through the reservoir area, forming the local lowest erosion base level with relative elevation differences of approximately 200-350 m. Following pumped-storage siting principles and considering the principle of maximizing the regulation storage capacity, two dam sites were selected on the left bank of the Guxian Reservoir area, with a preliminary proposed total installed capacity of 2 million kW.

3.4 New Unitary Multi-Energy Complementary Clean Energy Base

The aforementioned water, wind-solar, and energy storage resources are all clean energy sources. Analysis of each energy type' s generation characteristics reveals that wind power generation depends entirely on natural wind speed and intensity; photovoltaic generation is significantly affected by day-night cycles, seasons, weather, and temperature; and wind and photovoltaic output processes exhibit obvious intermittency, volatility, and randomness. Hydropower generation output and production vary with natural runoff conditions, but power stations possess certain regulation capabilities based on inflow, reservoir regulation performance, and reservoir operation patterns. Pumped-storage power stations start quickly, operate flexibly and reliably, provide peak shaving and valley filling functions, offer regulation capacity up to 200%, and achieve comprehensive efficiency of approximately 75%.

Currently, most power sources connect to the grid platform first, with the grid conducting unified dispatch according to each source' s characteristics to match target markets. This grid dispatch model implicitly defines priority levels for power sources, with random and fluctuating clean renewable energy sources like wind and solar receiving obviously lower priority than high-energy-consuming, high-pollution fossil energy sources. Due to operational mechanism limitations, grid peak-shaving capacity is limited, preventing large amounts of renewable energy from being accommodated, and wind and solar curtailment has been widespread in northwest China.

Effectively combining non-dispatchable wind-solar renewable energy with adjustable hydropower stations and better-regulated pumped-storage stations to build a new unitary multi-energy complementary clean energy base enables unified integration that meets multiple grid targets in advance, achieving stable output matching grid requirements and forming a new power-source-side regulated energy base. Leveraging the abundant water, solar, wind, land, and terrain resources in the Yellow River Basin' s Ω-shaped bend region, three unitary multi-energy complementary clean energy bases can be constructed. Internal main parameters and complementary types are shown in Table -1.

Table 3-1 Overview of Three Multi-Energy Complementary Clean Energy Bases in the Yellow River' s Ω-Shaped Bend Region

The energy bases rationally utilize the advantages of various internal power sources, integrate different energy types, employ multiple energy complementary technologies, and operate cooperatively. By comprehensively considering important parameters including total generation, curtailed wind-solar energy, pumped-storage electricity, and power output fluctuations, the bases conduct typical daily, weekly, monthly, seasonal, and annual energy output balancing in layered, zoned, and time-divided manners. This achieves complementary effects of reducing renewable energy curtailment rates, improving energy utilization efficiency, and enhancing power market matching. This represents an advanced measure for efficient utilization and intensive development of large-scale clean energy bases. The unitary multi-energy complementary clean energy base includes a dispatch coordination center (as shown in Figure [Figure 3: see original paper]-1) that aggregates various energy sources, bidirectionally regulates energy input and output, and optimizes energy combination patterns to meet target market electricity trading. The base internalizes local peak shaving, integrates water and electricity dispatch, enables renewable energy storage, and matches external markets. This new power source model fully utilizes the regulation performance of hydropower and pumped-storage stations to effectively resolve the instability and non-dispatchability defects of internal wind and photovoltaic energy, localize grid peak-shaving tasks, simplify grid dispatch levels, reduce grid peak-shaving pressure, solve output imbalance between peak and off-peak periods, reduce wind, solar, and hydro curtailment, and promote sustainable development of renewable clean energy industries.

4 Preliminary Economic Analysis of Multi-Energy Complementary Clean Energy Bases in the Yellow River' s Ω-Shaped Bend Region

Using the Heishanxia unitary multi-energy complementary clean energy base as a representative example, the base' s power generation costs were analyzed. Based on investment costs of 6,000 yuan per kW for Heishanxia hydropower, 5,500 yuan per kW for pumped-storage stations [7], 4,000 yuan per kW for photovoltaic stations, and 7,000 yuan per kW for wind power, preliminary estimates indicate total investment for the Heishanxia multi-energy complementary clean energy base of approximately 114.5 billion yuan. Total base costs include depreciation, materials, maintenance, wages and benefits, insurance, and other expenses. Based on cost parameters from similar power source structure projects and relevant economic evaluation standards, estimated annual total costs are 6.61 billion yuan, yielding a unit generation cost of 0.179 yuan/kWh.

Considering the limited accommodation capacity of the northwest power grid, the target market is positioned as Henan Province in central China, where power demand is urgent and the proportion of thermal power is higher. Henan grid' s current benchmark on-grid tariff for coal-fired units (including desulfurization, denitrification, and dust removal) is 0.3779 yuan/kWh. With a transmission fee of 0.08 yuan/kWh, the estimated on-grid tariff for the Heishanxia energy base is approximately 0.30 yuan/kWh, which is 0.121 yuan/kWh higher than the preliminary generation cost analysis. This indicates certain profit margins for the energy base. Detailed cost analysis for the Heishanxia multi-energy complementary clean energy base is presented in Table -1.

Table 4-1 Cost Analysis of Heishanxia Multi-Energy Complementary Clean Energy Base

5.1 Achieving Conservation and Intensive Water Resource Utilization

Constructing multi-energy complementary clean energy bases in the Yellow River' s Ω-shaped bend region can reduce water resource consumption and achieve conservation and intensive utilization. The Yellow River Basin is both an energy river basin and a water-deficient river basin. The upper and middle reaches host energy bases including Ningdong, Longdong, Ordos, and northern Shaanxi, which are dominated by fossil energy and consume enormous water volumes, approaching 1 billion m^3 under current conditions. Building Ω-shaped bend multi-energy complementary clean energy bases will fundamentally transform regional energy production patterns, reduce water consumption rates, and improve water resource utilization efficiency. Based on the current thermal power industry (air-cooled) water withdrawal quota index of 0.53 m^3/MWh [24], constructing these clean energy bases would save water annually.

5.2 Effective Reduction of Harmful Gas Emissions

Constructing multi-energy complementary clean energy bases in the Yellow River' s Ω-shaped bend region enables low-carbon, low-pollution development. China has dedicated significant efforts to air pollution control in recent years, substantially reducing heavy pollution days, but central regions including the middle Yellow River Basin still face considerable pressure. Building these clean energy bases can effectively reduce emissions of atmospheric pollutants including carbon dioxide, sulfur dioxide, nitrogen oxides, and dust. Based on 2019 national thermal power industry emission rates [25] of 838 g/kWh for CO_2, 0.187 g/kWh for SO_2, 0.195 g/kWh for NO , and 0.038 g/kWh for dust, constructing the Ω-shaped bend multi-energy complementary clean energy bases would reduce annual emissions by approximately 63.67 million tons of CO_2, 14,200 tons of SO_2, 14,800 tons of NO , and 2,900 tons of dust. According to recent paid auction results [26], carbon sink benefits alone could reach 1.2 billion yuan annually.

5.3 Effective Land Resource Utilization for Poverty Alleviation

Constructing multi-energy complementary clean energy bases in the Yellow River' s Ω-shaped bend region can effectively utilize northwest China' s desert land resources. This approach not only reduces wind and photovoltaic development costs but also enables farmers to obtain sustained benefits from otherwise barren land through equity dividends and employment arrangements, providing long-term support for resettled populations and local impoverished communities and effectively solving stability issues after poverty alleviation.

5.4 Contributing to Soil and Water Conservation

The middle Yellow River Basin urgently requires intensified control due to severe soil erosion. The extensive photovoltaic panels deployed in the Ω-shaped bend multi-energy complementary clean energy bases can not only convert solar radiation and regulate regional thermal balance to reduce slope storm erosion but also, when combined with loess plateau slope management, collect rainwater to promote vegetation growth, thereby contributing to soil and water conservation in the middle basin.

The Yellow River Basin is an energy river basin, and its Ω-shaped bend region is particularly important as a national energy production area. Applying the new unitary multi-energy complementary clean energy base construction model that effectively combines non-dispatchable wind-solar renewable energy with adjustable hydropower stations and better-regulated pumped-storage stations enables unified integration meeting multiple grid targets in advance, achieving stable output matching grid requirements and forming a new power-source-side regulated energy base. Leveraging the abundant water, solar, wind, land, and terrain resources in the Yellow River Basin' s Ω-shaped bend region to construct three unitary multi-energy complementary clean energy bases can not only promote conservation and intensive water resource utilization and ecological environmental protection for high-quality Yellow River Basin development but also holds significant meaning for accelerating energy structure adjustment and promoting the transition from fossil to clean energy output in western China.

References

[1] Hu Zhengyuan. Proposal for Establishing a Strategic Economic Zone in the Yellow River Ω-Shaped Bend [C]. China Think Tank Economic Observation (2013 No. 2). China International Economic Exchange Center, 2014: 148-154.
[2] Research on Development Strategy of Energy "Golden Triangle" [J]. Chinese Engineering Science, 2015, 17(09): 18-28.
[3] Fang Yuan, Zhang Wanyi, Cao Jiawen, Zhu Longwei. Current Status and Development Trends of China' s Energy Resources [J]. Mineral Resources Protection and Utilization, 2018(04): 34-42+47.
[4] National Bureau of Statistics. China Statistical Yearbook-2019 [M]. Beijing: China Statistics Press, 2019.
[5] Wu Yuming, Liu Shiyang. Research on Coupling Coordinated Development and Spatial Correlation of Cities in the Energy Golden Triangle Region [J]. Ecological Economy, 2020, 36(03): 78-84+91.
[6] Li Xinhang, Rao Shuling. Analysis of Causes and Countermeasures for China' s Wind and Solar Curtailment Issues [J]. Shanghai Energy Conservation, 2019(09): 719-723.
[7] Feng Li, Wang Sheliang. Significance and Main Challenges of Developing Pumped-Storage Power Stations in Northwest China [J]. Northwest Hydropower, 2014(02): 1-4+7.
[8] Lu Shuhui, Zhang Xudong, Zhang Zhihao. Analysis of Basic Characteristics

of Yellow River Sediment and Recommendations for Control Measures [J]. Water Resources Development and Management, 2018, 38(03): 29-32.
[9] Liang Xiaoxue. Pollution Characteristics and Source Analysis of Atmospheric Fine Particulate Matter in Ningdong Coal Chemical Base, China' s Energy Golden Triangle [D]. Lanzhou University, 2019.
[10] Li Jugen, Shi Lishan. Overview of China' s Hydropower Resources [J]. Hydroelectric Power, 2006(01): 3-7.
[11] China' s Clean Energy Development Capacity Needs Substantial Improvement [J]. Energy and Environment, 2020(02): 113.
[12] Wang Jinnan. Strategic Considerations for Ecological Protection and High-Quality Development in the Yellow River Basin [J]. Environmental Protection, 2020, 48(Z1): 18-21.
[13] Zhang Jinliang. Thoughts on Building the Foundation of Water Strategy for Ecological Protection and High-Quality Development in the Yellow River Basin [J]. China Engineering Consulting, 2020(05): 68-70.
[14] Zhang Jinliang. Water Strategy Considerations for Ecological Protection and High-Quality Development in the Yellow River Basin [J]. Yellow River, 2020, 42(04): 1-6.
[15] Zhang Wuding, Wang Pingping. Promoting Ecological Protection and High-Quality Development in the Yellow River Basin [J]. Environmental Economy, 2020(08): 60-63.
[16] Han Xiaoyan, Ding Lijie, Chen Gang, Liu Junyong, Lin Jin. Key Technologies and Research Prospects for Cascade Hydro-Wind-Solar Complementary Power Generation [J/OL]. Transactions of China Electrotechnical Society: 1-11 [2020-06-04]. https://doi.org/10.19595/j.cnki.1000-6753.tces.191797.
[17] Huang He, Qin Ling, Yu Yangyang, Wei Daowan. Intelligent Power Generation Technology for Hydro-Solar Multi-Energy Complementary Clean Energy [J]. Distributed Energy, 2020, 5(02): 21-
[18] Lu Jianfeng, Feng Junqi, Zhu Feifei. Practice, Problems and Countermeasures for User-Side Multi-Energy Complementary Development [J]. Shanghai Energy Conservation, 2020(03): 186-192.
[19] Keyvan Choopani, Reza Effatnejad, Mahdi Hedayati. Coordination of Energy Storage and Wind Power Plant considering Energy and Reserve Market for a Resilience Smart Grid [J]. Journal of Energy Storage, 2020, 30.
[20] Bilawal A. Bhayo, Hussain H. Al-Kayiem, Syed I.U. Gilani, Firas B. Ismail. Power management optimization of hybrid solar photovoltaic-battery integrated with pumped-hydro-storage system for standalone electricity generation [J]. Energy Conversion and Management, 2020, 215.
[21] Rituraj Singh Patwal, Nitin Narang. Optimal generation scheduling of pumped storage hydro-thermal system with wind energy sources [J]. Applied Soft Computing Journal, 2020, 93.
[22] Chen Wei, Ai Xin, Wu Tao, Liu Hui. Review of Research on Impact of Grid-Connected Photovoltaic Power Generation Systems on Power Grids [J]. Electric Power Automation Equipment, 2013, 33(02): 26-32+39.
[23] Yellow River Conservancy Commission. Yellow River Basin Comprehensive Plan (2012-2030) [Z]. Beijing: Ministry of Water Resources of the People' s

Republic of China, 2013.
[24] GB/T 18916.1-2012, Water Quota Part 1: Thermal Power Generation [S]. Beijing: China Standards Press, 2012.
[25] China Electricity Council, China Electric Power Industry Annual Development Report 2020 [R], 2020.
[26] Tianjin Emissions Exchange. Announcement of 2019 Tianjin Carbon Emission Allowance Paid Auction Results [EB/OL], http://www.tanpaifang.com/tanjiaoyi/2020/0610/71451.html, 2020-06-10.

Corresponding Authors:
Zhang Jinliang, E-mail: zhangjinliang@hebeu.edu.cn
Xing Jianying, E-mail: xingjy@yrec.cn

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