Development Concept of Integrated Energy Network and Hydrogen Energy Industry Based on Hydrogen Production Using Surplus Hydropower

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Abstract. The development of hydropower industry is progressing rapidly in China, and the installed capacity and power generation are increasing year by year. However, due to factors such as transmission channels and power grid peaking capacity, hydropower consumption in some areas is facing greater pressure. As an excellent medium for energy interconnection, hydrogen energy can play an important role in promoting hydropower consumption. This paper introduces the current status and trends of hydrogen energy development in major developed countries and China, and analyzes the current status of China’s hydropower abandoned water. Based on the production of hydrogen using surplus hydropower in the Dadu River Basin in Sichuan, an integrated energy network research plan including hydropower, electrolytic hydrogen production, storage and transportation, hydrogen refueling, and hydrogen-powered vehicles is proposed. At the same time, the development concept of hydrogen energy industry including hydrogen energy source economy, hydrogen energy industry ecosphere and hydrogen energy sky road in western Sichuan is also proposed.

1. Introduction
The past 10 years have been the peak period for the development of China’s hydropower industry, and the installed hydropower capacity and power generation continued to increase. By the end of 2018, China’s total installed hydropower capacity was approximately 350 million kW, accounting for 48.1% of China’s total renewable energy installed capacity and 18.4% of total power installed capacity, and 64.2% of China’s clean energy power generation and 17.1% of total power generation [1]. Both hydropower installed capacity and annual power generation continue to rank first in the world. Hydropower plays an increasingly important role in ensuring national energy security, clean transformation of the energy structure and green and low-carbon development. However, the problem of large-scale hydropower consumption still exists, owing to the uneven spatial and temporal distribution of hydropower resources, limited power transmission channels, and insufficient peak shaving capacity of the power grid. Hence, with the rapidly expanded scale of installed capacity, the more attention is paid to hydropower consumption in some parts of China (such as southwestern
China) [2, 3]. In 2017 and 2018, China’s abandoned water generation capacity was 51.5 billion and 69.1 billion kWh, respectively [4]. The difficulties of China’s hydropower consumption have restricted the transformation and upgrading of China’s energy production and consumption structure to low-carbon, non-carbonized, and clean, which is not conducive to China’s commitment to the emission reduction targets in the Paris Climate Change Agreement.

As a clean, efficient, safe and renewable secondary energy source, hydrogen can be obtained through primary energy, secondary energy and chemical fields, and can be stored and transported in various phase states. An important carrier of multiple energy supply systems based on energy [5]. According to the report of the World Energy Council, hydrogen is divided into three categories according to the source of production: gray hydrogen, blue hydrogen and green hydrogen. Gray hydrogen accounts for 96% of the current main source of hydrogen, mainly from fossil fuels, such as steam methane reforming (SMR) or coal gasification. The cost of hydrogen produced by this process is lower, but the carbon intensity is the highest, so the social acceptance is the lowest. Blue hydrogen is mainly produced by steam methane reforming or coal gasification with carbon capture and storage (CCS), which has low carbon intensity, high cost, and higher social acceptance. Green hydrogen is produced by electrolysis or pyrolysis using renewable energy. It has zero carbon dioxide emissions and is expensive, but it has the highest social acceptance [6]. Therefore, the use of surplus hydropower for hydrogen production (mainly using electrolyzed water for hydrogen production) can not only realize the non-carbonized and clean production of hydrogen, but also expand the surplus hydropower consumption channel, which has the significant potential to promote China’s energy transformation and development in the new era.

At present, hydrogen fuel cell powered vehicles are the main users of hydrogen energy (in the future, distributed hydrogen fuel cell energy storage facilities will also be included), and the demand for hydrogen is more discrete [7]. Therefore, it is necessary to comprehensively apply modern information technologies such as mobile Internet, Internet of Things and big data, incorporating all aspects of hydropower generation, electrolytic hydrogen production, hydrogen storage and transportation, hydrogen refueling, and hydrogen-powered vehicles, to carry out research on the integrated energy network based on production of hydrogen using surplus hydropower, and realize the safe, efficient and economic operation of the hydrogen production system, and promote the construction of the hydrogen energy industry ecosystem.

2. Development Status and Trend of Hydrogen Energy

2.1. Overview of Hydrogen Energy Industry Development in Major Developed Countries

The continuous evolution of global climate warming has continued to increase the impact on human production and life, and the implementation of a clean energy development strategy is imminent. Hydrogen energy is internationally recognized as the most ideal clean energy and will become an important part of the future green energy system in the world. Since the 1990s, major developed countries and international organizations have invested heavily in the research and development of hydrogen-related technologies. Hydrogen economy has become a new field of energy competition in the 21st century [8].

2.1.1. USA. From the height of national sustainable development and security strategy, the United States has formulated a long-term development strategy for hydrogen energy. From 2000 to 2040, every 10 years as a stage, respectively: technology, policy and market development stage; transition to the market stage; market and infrastructure expansion stage; into the hydrogen economy era.

2.1.2. Japan. Facing the increasing price of fossil energy and its domestic energy gap, as the country with the most patents in the field of hydrogen fuel cells in the world, the Japanese government has clearly put forward a hydrogen society country that advocates the promotion of the use of hydrogen energy in the energy basic plan Strategy and development roadmap. In 2014, the Japanese government
announced the development roadmap for hydrogen energy and fuel cells: the first phase (by 2025), mainly to promote the widespread application of fuel cells; the second phase (2025-2040), to promote fuel cell power plants and establish hydrogen supply chain for overseas energy supply; the third stage (after 2040), establishes a hydrogen supply chain with no CO$_2$ emissions.

2.1.3. EU. The European Union launched the “European Research Area” project in 2003, which included the “European hydrogen energy and fuel cell technology platform.” In November 2016, the European Commission passed clean energy legislation to support the development and application of hydrogen and fuel cells.

According to the plans of major developed countries in the world for the application of hydrogen energy, it can be seen that the next 10 years will be a period of explosive growth in the application of hydrogen energy, and the hydrogen energy industry has become a new hot spot in the energy field.

2.2. Development of Hydrogen Energy Industry in China

The research of hydrogen energy in China began in the early 1960s, and was mainly used in the development of oxyhydrogen fuel cells in the aerospace field and the production of liquid hydrogen fuel. Beginning in the 1970s, hydrogen was developed as an energy carrier and a new energy system. In 2003, China, as one of the founding member countries, signed the “International Partnership Program for Hydrogen Energy Economy”. In recent years, China has done a lot of work in hydrogen energy economic research and development, international cooperation in related fields, and various demonstrations and publicity. China’s hydrogen energy development technology has gradually entered the world’s advanced ranks. As of March 2019, 14 provinces (municipalities) nationwide have carried out hydrogen energy industry layout and promotion. Most of the regions have issued relevant industry support policies and implemented a batch of fuel cell or vehicle industries to promote the construction of hydrogen refueling stations and actively carry out demonstration operations.

3. The Problem of Hydropower Curtailment in China

3.1. Current Status of China’s Hydropower Curtailment

In recent years, China’s installed capacity of renewable energy such as hydropower, wind power and photovoltaic power generation has been increasing, but due to factors such as slowing economic growth and lagging power grid capacity construction, the average utilization hours of renewable energy power generation equipment is not high, and remain highly abandoned [9], as shown in figure 1. Among them, the surplus hydropower in 2018 was 69.1 billion kWh, which was 17.6 billion kWh higher than 2017. Large-scale renewable energy storage, especially the storage of surplus hydropower, is still an important problem to be solved urgently in China’s current healthy development of energy.

3.2. Current Status of Hydropower Curtailment in Dadu River Company

The Dadu River Basin in Sichuan ranks fifth among the 13 largest hydropower bases in China. The main stream is planned to have 28 cascade hydropower stations with a total planned installed capacity of approximately 32.4 million kW. Guodian Dadu River Hydropower Development Co., Ltd. (referred to as “Dadu River Company”) is the main body of the development of cascade hydropower stations in the main stream of Dadu River, being responsible for the development of 17 cascade hydropower stations. The company’s current installed capacity is 11.74 million kW, which acts a strong support role for the safe and stable operation of the Sichuan power grid.

Sichuan’s power grid has large hydropower installations, small market capacity, and fierce competition. The power storage capacity of the power station affiliated to Dadu River Company is small, so it is difficult to consume the hydropower during the flood season, resulting in a continuous increase in abandoned hydropower, as shown in figure 2. If part of the surplus hydropower of Dadu River Company can be used for hydrogen production, the surplus electric energy can be converted into
hydrogen energy which is easier to store or further converted into other chemical energy, thereby large-scale, quarterly surplus electric energy storage will be achieved.

![Figure 1. China’s renewable energy abandonment trend in recent years.](image1)

![Figure 2. Abandoned hydropower of Dadu River Company’s power station in recent years.](image2)

3.3. Problems Faced by Hydrogen Production Using Surplus Hydropower

3.3.1. The Cost of Producing Hydrogen from Electrolyzed Water Is Too High. The cost of hydrogen production from electrolyzed water mainly includes electricity cost, equipment depreciation and labor cost, of which electricity cost accounts for 80% to 90% of the total cost. Since electrolyzed hydrogen production enterprises implement industrial electricity tariffs, urgent support policies are needed to further reduce the electricity price for hydrogen production. In 2017, the Sichuan Provincial Development and Reform Commission document pointed out that “for the green high-energy industries such as electrolytic hydrogen, the transmission and distribution price is charged at 0.105 yuan per kWh compared to the remaining electricity transmission and distribution price in Tibetan areas,” creating a good policy and economic foundation for business development. But the implementation of the policy still needs the support of grid companies.

3.3.2. The Distance Sensitivity of Hydrogen Transportation Cost Is High. If considering the production of hydrogen near the hydropower station, the transportation cost is about 5.6 yuan per kg and per 100 kilometers. The power station in the Sichuan Dadu River Basin is far from the main cities. Most of them exceed the critical point of the economic transportation distance of hydrogen (not more than 200 kilometers), and the comprehensive cost will exceed the user-side hydrogen production plan.

3.3.3. Market Application Needs to Be Cultivated. The traditional hydrogen production supply chains such as coal-to-hydrogen and industrial by-product hydrogen are mature and complete, and electrolyzed water-to-hydrogen does not yet have sufficient advantages to replace it. Incremental markets such as hydrogen fuel cell vehicles and the semiconductor industry are in the early stages of commercial promotion, and market demand has not yet been fully released. In the field of civil natural gas, there is a lack of testing and application standard systems for hydrogen mixing in pipeline networks, and commercial applications need further research and exploration.

4. Integrated Energy Network Based on Hydrogen Production Using Surplus Hydropower

Affected by many factors such as installed capacity, power grid construction, and user-side demand, the overall abandonment of hydropower at Dadu River Company is more prominent, and it is increasingly urgent to find new ways to consume electricity [10]. Therefore, the use of surplus hydropower for large-scale hydrogen production as one of the options was included in the company’s agenda. At the same time, in order to provide decision support for the company’s hydrogen energy
industry planning and development strategy, Dadu River Company launched an integrated energy network research work based on hydrogen production using surplus hydropower.

4.1. Research Content and Technical Route

This project is mainly carried out from four aspects: the technical and economic model of large-scale surplus hydropower hydrogen production, the typical design of the surplus hydropower hydrogen demonstration project, the research and development of high-efficiency hydrogen production equipment, and the feasibility and the typical design of the integrated energy network demonstration project.

4.1.1. The Technical and Economic Model of Large-Scale Surplus Hydropower Hydrogen Production.

Complete the key technical analysis of large-scale surplus hydropower production firstly, then establish the economic operation model of electrolyzed water and hydrogen storage units, and finally develop the surplus hydropower generation decision support database, in order to provide decision support and analysis methods for hydropower hydrogen production and hydrogen storage projects.

4.1.2. The Typical Design of the Surplus Hydropower Hydrogen Demonstration Project.

At first, the operation simulation and main index design of the hydrogen storage unit for hydropower generation are carried out, and then the safety evaluation method of the hydrogen storage system is proposed. Finally, modern information technologies such as the Internet of Things, mobile internet and big data are comprehensively applied to carry out integrated energy network simulation and operation optimization technology, complete the feasibility study and typical design of large-scale surplus hydropower hydrogen production demonstration project.

4.1.3. The Research and Development of High-Efficiency Hydrogen Production Equipment.

First, develop key materials and new structures for high-temperature solid oxide electrolysis cell (SOEC), and then develop integrated test technology of SOEC. Aiming at the new structure of SOEC, analyze the reliability characteristic parameters, formulate reliability indexes, improve the reliability of the SOEC system, and improve the integrated test technology level.

4.1.4. The Feasibility and the Typical Design of the Integrated Energy Network Demonstration Project.

Based on the above results, propose the integrated energy network simulation and decision-making optimization technology. Finally, carry out the feasibility analysis and typical design of the hydrogen energy integrated demonstration project, including hydropower generation, hydrogen production-transportation-storage-refueling, and fuel cell vehicle operation.

4.2. Technical Innovation

In terms of device research and development, the development of test technology for high-efficiency hydrogen generating units aims to reduce the power consumption of hydrogen production and catch up with the technique forefront, and finally lays the foundation for the inter-seasonal energy storage research based on the high-temperature SOEC hydrogen production technology.

At the engineering design level, research and development of optimized control technologies for the operation and safety of hydrogen production from hydropower. Under the limited power input, with the power plant peak shaving, it maximizes the output of hydrogen production and guarantees the safety and reliability.

At the level of system simulation, the integrated energy network simulation and decision-making assistance technology for is proposed. Using the hydrogen supply chain network to cooperate with the operation of the hydropower system, the optimization of green hydrogen energy infrastructure investment decisions is supported.
4.3. Expected Economic and Social Support Benefits

4.3.1. Economic Benefits. Promote the consumption and clean and safe storage of surplus hydropower, increase the electricity sales and hydrogen sales revenue of power generation enterprises, and at the same time reduce the cost of hydrogen used by terminal hydrogen users. In the future, distributed hydrogen fuel cell energy storage devices can also be included in system management to participate in peak shaving and valley filling of the power grid, improve the quality of the power grid operation, and reduce the energy cost of end-use customers.

4.3.2. Social Benefits. Partial replacement of fossil energy can reduce greenhouse gas and pollutant emissions, and help promoting green and low-carbon economic and social development. At the same time, the accumulated construction and operation experience of the integrated energy network demonstration project will help formulate and improve the relevant standards of the hydrogen energy industry, promote the construction of the hydrogen energy industry ecosystem, and further accelerate the development of China’s hydrogen energy industry.

5. Hydrogen Energy Industry Development Conception of Dadu River Company

In order to broaden the channels for surplus hydropower consumption and realize the large-scale development of the hydrogen energy industry, Dadu River Company is actively constructing the “source economy” of hydrogen energy, actively creating a hydrogen energy industry ecosystem, and is the first one to propose the creation of “Hydrogen Energy Sky Road in Western Sichuan”.

5.1. “Source Economy” of Hydrogen Energy

Dadu River Company will use part of the surplus electricity of its affiliated hydropower stations to produce hydrogen. The water produced by the hydrogen application will return to the natural water system through the atmospheric circulation, thereby constructing the energy and water circulation using hydrogen as a medium, as shown in figure 3. Dadu River Company’s hydrogen production project can provide clean hydrogen for the hydrogen users in the neighboring areas, which helps to build a clean hydrogen energy recycling industrial chain and ecosystem.

5.2. Hydrogen Energy Industry Ecosystem

The core link of the hydrogen energy industry ecosystem is the use of clean electricity to produce hydrogen, as shown in figure 4. Taking the Dadu River surplus hydropower hydrogen production project as the center, comprehensive application of advanced technologies such as cloud computing, big data, Internet of Things, 5G and Beidou navigation and positioning system can build a hydrogen energy vehicle intelligent operation platform, which can provide intelligent decision support for power plants, hydrogen production and refueling stations, and transportation companies to formulate hydrogen production and consumption plans. The intelligent operation platform can integrate wind power, photovoltaic and other renewable energy power plants to realize the multi-energy complementary hydrogen production.

Taking the intelligent operation platform as the core and hydrogen energy as the link, it can form the outer circle of the hydrogen energy industry chain including renewable energy, advanced manufacture, green chemical, new energy vehicles and other industries. The outermost layer realizes industrial cultivation, capital investment, talent gathering, and enterprise gathering through the hydrogen energy industrial fund and hydrogen energy industrial park.

5.3. Hydrogen Energy Sky Road in Western Sichuan

The Chengdu-Ya’an highway and the Ya’an-Panzhihua highway are the main communication routes between Sichuan and Yunnan. The Dadu River and the Yalong River Basin passing by along the route are rich in hydropower, wind power and solar energy resources. Among them, nearly 20 million kW of hydropower have been put into operation, which provides an adequate clean energy foundation for the
construction of the “Hydrogen Energy Sky Road in Western Sichuan”. This “Sky road” will take Chengdu as the starting point, reach the end of Panzhihua via Ya’an and Xichang. The project aims to use the abundant renewable energy along the Chengdu-Ya’an and Ya’an-Panzhihua highway to produce hydrogen, and install hydrogen stations along the way to refuel the hydrogen vehicles running on the road (figure 5). The concept combines renewable energy and hydrogen energy transportation perfectly, while promoting the consumption of renewable energy, it reduces the consumption of fossil energy and the emission of greenhouse gases and atmospheric pollutants.

Figure 3. Using hydrogen as a medium to realize the circulation of water and energy.

Figure 4. Hydrogen industry ecosystem based on surplus hydropower for hydrogen production.

Figure 5. Route diagram of the Hydrogen Energy Sky Road in Western Sichuan.

6. Conclusion and Suggestion

China’s hydropower installed capacity and power generation capacity continue to grow, and the role of clean energy substitution is increasingly prominent. However, due to factors such as the spatial and temporal distribution of resources, the capacity of the distribution channels and the balance of supply and demand of social power, hydropower has relatively serious abandoned water in some areas and some periods. This phenomenon is not conducive to the low-carbon, non-carbonized and clean transformation of China’s energy structure, and the completion of related energy saving and emission reduction targets on time. As a clean, efficient, safe and renewable secondary energy carrier, hydrogen can be used for large-scale conversion and storage of hydropower.

The main body of investment and operation of hydropower, by carrying out integrated energy network research based on surplus hydropower hydrogen production, merges efficient hydropower
intelligent dispatch technology, efficient electrolytic hydrogen production technology, safe and reliable hydrogen storage and transportation technology and advanced information technology, can provide intelligent decision support for the operation and consumption subjects of the hydrogen energy industry chain while achieving the surplus hydropower consumption.

The use of surplus hydropower to produce hydrogen has expanded the consumption of renewable energy, which is conducive to accelerating China’s energy production and consumption revolution, and is of great significance to the transformation and development of energy in the new era. Although some explorations and practices have been carried out [10], there are still considerable challenges in system development strategies, hydrogen energy infrastructure construction, key technologies for hydrogen storage and transportation, cost control, and business models. Therefore, it is necessary to further strengthen the research and development of hydrogen energy industrial strategy, key technologies and core equipment to ensure the orderly, healthy and sustainable development of the industrial chain coupling renewable energy such as hydropower and hydrogen energy.

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