Research Article

Research on the Impact of Hydro-PV Complementary System Operation on Power Grid Based on New Energy Consumption

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Considering the random, intermittent, and periodic characteristics of photovoltaic (PV) power generation, its active output must be compensated and regulated by other conventional power sources. Taking the Longyangxia hydropower station as an example, this study models the output of PV generator sets and hydropower units under different conditions, taking into account the influence of weather and seasonal factors on the characteristics of PV power generation and hydropower generation. We also analyze the hydro-PV resource distribution and output characteristics of Longyangxia and construct the integration of hydro-PV complementary in Longyangxia. The impact of hydro-PV integration on the power grid is discussed in terms of other new energy consumption and peaking capacity, and the impact of the Yellow River water dispatch and downstream gradient power generation. It is demonstrated that hydropower is a good complementary resource to PV power generation, which not only improves the quality of the grid but also enhances the new energy consumption capacity. Through the construction of the Longyangxia hydro-PV complementary project, it can increase the economic benefits of the power grid and play an important role as a reference for subsequent projects.

1. Introduction

Fossil energy is the main cause of global warming, the hole in the ozone layer and other ecological problems. With the depletion of fossil energy sources and the gradual deterioration of the human living environment, the development of a clean and low-carbon sustainable development concept is a globally accepted trend. The vigorous development of clean and renewable energy has become an important step in the reform of the energy structure [1, 2]. As a clean, renewable, and green energy source, solar energy is not only abundant but can also be used to generate high-quality electricity without pollution. However, photovoltaic (PV) power generation is often influenced by season, temperature, day and night, and cloudiness and exhibits strong randomness, intermittency, and periodicity [3]. PV must be compensated and regulated for its active output by other conventional power sources [4]. Hydropower has good cleanliness, flexibility and peaking, and frequency regulation capabilities, and hydropower units can regulate the active output of PV stations [5]. Coordinated power generation using complementary hydro-PV operations can maximize energy use and meet the requirements of grid power dispatch [6].

As PV power generation has entered a boom period, many new cell and passivation technologies have emerged [7–9]. In order to promote the development and use of solar energy, Western developed countries have actively formulated various preferential policies to encourage the development of solar PV power generation. Prediction of PV
output is necessary to take into account the influence of external factors on PV output. Many mathematical models exist to predict PV output [10, 11]. Morozova et al. [12] proposed a multiple linear regression model (MRM) to reconstruct the daily mode amplitudes and improve the accuracy of the optical power prediction system. Ziadi et al. [13] proposed an optimization technique based on load demand and PV generation forecast values to reduce the impact of forecast errors on power generation. Yan et al. [14] proposed a real-time prediction model for PV system output power and energy efficiency, used the prediction model to classify the output power in different seasons and months, and achieved better results in certain areas. Considering the strong randomness and fluctuation of PV output, the flexible dispatch of hydropower can be used to smooth out the fluctuation of PV output, which can promote PV consumption and improve the safety of grid operation. However, PV access will also have an impact on hydropower operation. In recent years, a great deal of research has been carried out on the coordination and the economics of complementary hydro-PV complementary system [15–17]. The coordinated development of hydro-PV complementary focuses on output power fluctuations and operational efficiency. In [18], a multienergy complementary long-term multiobjective optimization model is developed with the objectives of total annual system power generation and smoothing of system output power fluctuations. Frank et al. [19, 20] carried out research work on key technologies such as the theory of hydro-PV complementary balance principle and the coordinated operation control scheme of hydro-PV complementary. Li and Li [21] recommended that advanced technologies such as high-power modules, string inverters, and wireless communication can be promoted and applied in hydro-PV complementary projects to improve the operational efficiency of the projects. Research on the economics of hydro-PV complementary focuses on the goal of maximizing returns with minimal input costs. Beluco et al. [22] proposed a theory of limiting performance that investigates the impact of different degrees of energy resource complementary in time on the efficiency performance of hydro-PV station and the economic performance of hybrid generation systems. Tan et al. [23] proposed a day-ahead complementary operation model and an optimal real-time load allocation model to derive the power generation under the stochastic characteristics of PV, and assessed the benefits and risks of the complementary operation. Chen [24] proposed a dispatch measurement rate for hybrid generation based on complementary characteristics, established a minimum cost optimization model, and analyzed the economy of the system under different operating modes. In summary, hydro-PV complementary is based on the study of stochastic optimization problems, and considering the study of optimal dispatch under different scenarios (different seasons, weather conditions, and different time periods) is an effective solution to the stochasticity of complementary systems [25–27]. At the same time, the strong uncertainty and high-power electronics brought by the access of new solar energy sources to the grid system operation need to be explored in depth [28–30].

Based on the above analysis and discussion, the main contributions of this study, using the Longyangxia power station as the subject of study, are as follows: (1) the annual, monthly, and daily output characteristics of hydropower station and PV power station are fully studied based on the effects of day and night, season, weather, and temperature. (2) A hydro-PV complementary system is constructed based on the hydro-PV output characteristics under different conditions, and the output coordination of the integrated hydro-PV complementary system is studied. (3) The impact of hydro-PV complementary integration on the power grid was analyzed, confirming that hydropower is a good complementary resource to PV power generation, which not only improves the quality of the power grid but also enhances the capacity of new energy consumption.

The rest of this study is as follows: Section 2 constructs a system diagram of a complementary hydro-PV power station (as shown in Figure 1), introduces the mathematical model of hydropower and PV output, and analyzes the output characteristics of hydro and PV under different conditions. Section 3 analyzes the annual and monthly power generation characteristics of the PV power station and the operation mode of hydro-PV complementary based on the actual situation of the Longyangxia power station. The fourth section discusses the impact of hydro-PV integration on the power grid in the context of complementary hydro-PV operation. In the last section, the work of this study is summarized and the outlook is given.

2. Model

2.1. System Construction. The hydro-PV complementary power station is regarded as a “virtual hydropower unit,” which is connected to the hydropower station and regulated by the hydropower generator set, and the power generated by the combination of the two sources is sent to the grid using the outlet channel of the Longyangxia hydropower station. The main factor affecting hydropower output is the overflow of hydropower units; the main factor affecting the output of PV power is the PV radiation. However, the PV radiation greatly fluctuates under different weather seasons, which causes the unsmooth PV output. Considering the rapid regulation ability of hydro generator set, it can be used to adjust the active power output of PV power station for hydro-PV complementary power generation, which can effectively make up for the shortage of independent PV power station and improve the safety and stability of power system.

2.2. Mathematical Model

2.2.1. Hydropower Output. Hydroelectric power is the process of converting the potential energy of water into rotating mechanical energy and eventually into electricity. The output power of hydropower is actually the output power of the generator set. The output power of hydropower is related to the overflow, head, and conversion efficiency of the hydropower unit. The head will change with the water level of a hydropower station, so the head loss can be ignored.
in the calculation of hydropower generation. The upstream water situation of a hydropower station determines the power generation flow of the hydropower unit. The hydropower conversion efficiency is what determines the size of the output power of the hydropower unit, and the hydropower output power is as follows:

\[ P = 9.81QH\eta, \quad (1) \]

where \( H \)–effective head, \( Q \)–flow rate, and \( \eta \)–power station unit efficiency.

2.2.2. PV Output. The PV power generation is a PV effect, which uses the absorption of PV by semiconductors to produce a directional movement of charge and ultimately current and electric potential. The PV output is influenced by the intensity of solar radiation, the temperature coefficient of the PV module, and other parameters. As long as the corresponding PV intensity and ambient temperature are given for each moment, the PV power output can be calculated from the following equation for the corresponding:

\[ P_V = \left( \frac{Y_V R_T}{R_{STC}} \right) \left[ 1 + \eta (T_C - T_{STC}) \right] \times (1 - \gamma), \quad (2) \]

where \( P_V \)–actual output of the PV unit, \( Y_V \)–rated output of the PV unit, \( R_T \)–actual intensity of solar radiation, \( R_{STC} \)–standard test conditions PV intensity, \( \eta \)–the temperature coefficient of the PV module, usually taken as 0.35%/C, \( T_C \)–the actual temperature of the PV module, \( T_{STC} \)–the temperature under standard test conditions, usually taken as 25°C, and \( \gamma \)–the shading coefficient of the PV array, usually taken as 10%.

Considering the different intensities of solar radiation in different areas, the PV array is always perpendicular to the direct rays of the sun. Therefore, the actual PV intensity at different times can be calculated based on the geometric relationship between the solar incidence angle of the sun at different orientations, as seen in the following equation:

\[ \int_{t=t_0}^{t=t_1} R_T \sin(\theta(t))dt = R_H \times 24, \quad (3) \]

where \( R_T \)–the average daily PV intensity on the horizontal plane, \( \theta \)–the hourly angle of solar incidence with respect to the horizon, which is a function of time \( t \), \( t_0 \)–the time of sunrise, and \( t_1 \)–the time of sunset.

2.3. Output Characteristics

2.3.1. Annual Output

**PV Station.** The PV power stations are influenced by day and night, season, weather, and temperature, and their power generation characteristics show strong fluctuations and randomness. The stronger the solar radiation, the greater the output of the PV station. Using a typical year of 8,760 hours of annual generation, the month-by-month radiation and output of the PV power station were analyzed and the results are shown in Figure 2. As can be seen in Figure 2, radiation levels are high from April to August, with average output reaching around 725 MW; from January to February, with lower radiation levels in October-December, the monthly output level is around 400 MW.

**Hydropower Station.** Hydropower station can be divided into dry water year, average water year, and abundant water year by the amount of water coming. The average output of a hydropower station in an abundant water year is greater than the average output in an average water year that is significantly greater than the average output in a dry water year. The average year is taken as an example to analyze the hydropower output in each month, as shown in Figure 3. The average annual output of the average water year station is 754.2 MW, and the average monthly output is 450.2–1109 MW. Among them, April, and August and October output are larger, and May to July output is smaller.

2.3.2. Monthly Output

**PV Station.** The results of the analysis of the radiation and output of the PV power station in a typical month of January and July are shown in Figure 4. In terms of electricity generation, the average output in July was approximately more than twice the average output in January. Overall, the daily output of PV power station under a typical month showed greater volatility; July was more volatile overall, with a more random output profile.

**Hydropower Station.** Typical months, January and July, were used to analyze the output of the hydropower station, and the results are shown in Figure 5. As can be seen in Figure 5, the output of the hydropower station in July is significantly greater than that in January due to the amount of water coming in, with the average output in July being approximately twice as high as that in January; power station output was more stable and less volatile in the second half of July.

2.3.3. Daily Output

**PV Station.** The daily radiation and daily output of the PV power station were analyzed for a combination of summer, winter, sunny, and cloudy conditions, and the results are

![System diagram of the hydro-PV complementary power station.](image-url)
shown in Figure 6. Within a day, power generation from the PV power station is influenced by the weather and the seasons, with a high degree of intermittent regularity. The daily output curves of a PV power station under different conditions show that PV power station generates electricity from 6 to 21 pm in summer and from 9 to 19 pm in winter. In sunny summer, the output varies in the range of 0–820 MW; the output on cloudy days in summer varies in the range of 0 MW~140 MW; the output on sunny days in winter varies in the range of 0 MW~450 MW; and the output on cloudy days in winter varies in the range of 0 MW~125 MW.

Hydropower Station. The results of the analysis of hydropower station output in summer, when water is plentiful, and in winter, when it is depleted, are shown in Figure 7. Hydropower output is basically stable at around 900 MW in summer; winter hydropower output shows a range of volatility, with output varying between 300 and 645 MW throughout the day.

3. Examples

3.1. Project Overview. The Longyangxia hydropower station is the “leading” power station in the development plan of the Yellow River Longqing section. The power station is located at the entrance of the Longyangxia and has good regulation characteristics. The operation and dispatch are based on the “using water to set electricity and electricity to set water” approach, and the readily available reservoir capacity can fully compensate and regulate the PV station. The hydropower is equipped with four hydroelectric-generating units with a single capacity of 320 MW, with a total installed capacity of...
About 850 MWp of Longyangxia hydro-PV power station will be built in the long term, 320 MW in the first phase, and the main task is to generate electricity.

The compensation regulation of the hydropower station to the PV power station is based on intraday compensation, which does not change the total daily and annual and monthly outflows from the Longyangxia hydropower station and does not affect the joint compensation operation and dispatch of the Longyangxia and Liujiagxia reservoirs. Fluctuations in the flow of the hydropower station after hydro-PV complementary can be fully counter-regulated by the downstream Laxiwa Hydropower Station, with minimal impact on the operation of the Longyangxia hydropower station and the downstream terrace stations. Through the compensatory regulation of the Longyangxia reservoir, the Longyangxia hydro-PV complementary has a certain impact on the peaking capacity of the undertaking system, but it is not significant relative to the peaking capacity of the Qinghai Yellow River step hydropower station.

3.2. Power Generation Characteristics of PV Power Station

3.2.1. Annual Characteristics. Based on the solar radiation data in the vicinity of the station and the power output during the operation period from 1998 to 2006, the average
annual power output of the PV power station during 1998-2006 is estimated as shown in Figure 8.

The variation in the average annual power generation of the PV power station shows that the station was relatively stable in 1998 and from 2000 to 2004, generating approximately 132 million kWh of power. In 1999, 2005, and 2006, there were sudden changes; the maximum annual average generation capacity in 2000 was approximately 132.5 million kWh; the minimum annual average generation capacity in 1999 was approximately 128.97 million kWh; and the annual average generation capacity during the operation period from 1998 to 2006 was approximately 130.98 million kWh. The minimum annual power generation is about 98% of the annual average power generation, and the maximum annual power generation is about 2% of the annual average power generation. The annual change in power generation is relatively stable.

3.2.2. Monthly Characteristics. The distribution of solar energy resources has an obvious seasonal difference, which leads to obvious seasonal variation in PV power station output. The month-to-month changes in power generation in an average year are analyzed (take 2001, for example), as shown in Figure 9.
The graph of the month-to-month variation analysis shows that the average monthly power generation is around 109.03 million kWh. Solar cell modules increase as the temperature decreases. In winter, the solar radiation is small, the temperature is low, and the power generation is large ranging from 1.18 million kWh to 121 million kWh. Higher temperatures during the summer months when solar radiation is at its strongest lead to a drop in power generation, with the power station generating approximately 98.3 million kWh during the summer months, and the smallest of these was generated in June, at approximately 89.9 million kWh. During the operation of the power station, the month-to-month variation in power generation from the PV power station is more pronounced, with larger amounts of power generated in the winter and spring seasons and smaller amounts in the summer and autumn.

3.3. Operational Models for Hydro-PV Complementary. Based on the operational characteristics of the Longyangxia hydropower station at different times, a typical output curve is selected and adjusted to meet the peak regulation requirements of the grid at different times. The average output of the PV is calculated based on the predicted daily PV generation, and the typical output curve is shifted upward based on the average PV output to form the total output of the hydro-PV complementary. The hydro-PV complementary output curve for the Longyangxia is shown in Figure 10.
In actual operation, the fixed scheduling curve operation and the hydro-PV total output-giving method can be used. The fixed scheduling curve operation mode only operates according to the scheduling curve, the PV operates according to the power generation capacity, and the hydropower is complemented by hydro-PV according to the actual situation of PV operation to meet the total hydro-PV output requirements. The total output of hydro-PV is given according to the needs of grid operation and water dispatch, and the dispatch curve is modified at any time, or the total output of hydro-PV is ordered, and the hydropower is complemented by hydro-PV according to the actual situation of PV operation to meet the total output of hydro-PV.

4. Analysis of the Impact of Complementary Hydro-PV Operation on the Power Grid

4.1. Analysis of the Impact on Other New Energy Consumption and Peaking Capacity. The installed capacity of the PV power station in the Qinghai power grid is much larger than that of other new energy sources. Therefore, this study mainly considers PV power generation in the Qinghai grid.
In order to analyze the impact of hydro-PV complementary on the consumption and peaking capacity of other new energy sources, the system peaking capacity undertaken before and after the Longyangxia hydro-PV complementary is compared, respectively. The maximum output process of the 320 MW PV power station in July and December before hydro-PV complementary is used as the basis, and the output process of the planned 4,100 MW PV installation in 2015 is obtained by disproportional calculation of its output in each hour, and the output process is used as a negative load to correct the daily load curve, and the load curve of the Qinghai power grid in July and December after considering the PV power station is shown in Figure 11.

![Figure 11: Daily load curve of the Qinghai grid considering PV power station under a typical month.](image)

In order to analyze the impact of hydro-PV complementary on the consumption and peaking capacity of other new energy sources, the system peaking capacity undertaken before and after the Longyangxia hydro-PV complementary is compared, respectively. The maximum output process of the 320 MW PV power station in July and December before hydro-PV complementary is used as the basis, and the output process of the planned 4,100 MW PV installation in 2015 is obtained by disproportional calculation of its output in each hour, and the output process is used as a negative load to correct the daily load curve, and the load curve of the Qinghai power grid in July and December after considering the PV power station is shown in Figure 11.

Considering the maximum power generation capacity of the 4,100 MW PV power station installed in the Qinghai grid in 2015, the load trough in the Qinghai grid shifts from around 4 am to around 13:00–15:00 in July and December. The peak-to-valley differential increased from 1330 MW to 3320 MW in July and from 1740 MW to 4100 MW in December. With a projected installed capacity of 12,050.4 MW in 2015, Qinghai province is fully capable of regulating peak-to-valley differences during periods of abundant water and dry water.

Before the hydro-PV complementary Longyangxia hydropower station takes on the task of system peaking, the hydropower station needs to generate as little power as possible during the time when the PV power station is generating more power. If the Longyangxia hydropower station carries a system base load of 200 MW, the hydropower station will need to operate with 200 MW to match the PV station; if the hydropower station does not carry the system base load, the hydropower station will need no load running the PV power station operation when the PV power station is generating at maximum output. After the hydro-PV complementation, the combined hydro-PV power supply needs to first consider the operation of the PV power station to generate electricity and compensate for the nearby PV power station. When compensating other PV power stations for power generation after hydro-PV complementary, it is necessary to consider whether the hydropower station in the combined power supply has a base load generation requirement. If this is required, the hydropower station will need to be reduced to base load generation to reduce the output of the combined hydro-PV power supply; if not, the hydropower station will operate at no load. However, considering that the combined power supply 320 MW PV power output is also larger, the output cannot be reduced to below the combined power supply PV power output; otherwise, 320 MW PV power abandonment is needed to compensate for other PV power stations. Therefore, the compensation capacity of the combined power supply to other PV power stations in the Qinghai.
power grid is reduced after the hydro-PV complementation, and the reduction is the amount of compensation needed for the combined power supply of 320 MW PV power station.

Therefore, before and after the hydro-PV complementary are hydropower to PV power station compensation consumption. Hydropower gives full play to its regulating role and achieves the purpose of increasing the grid system’s PV consumption. The integration of hydro-PV complementary to the Longyangxia is carried out on the premise of meeting the comprehensive utilization requirements of the Longyangxia and its gradient power stations for flood control, power generation, and irrigation, without changing the role and status of the Longyangxia hydropower station in the power system or affecting the power generation benefits of the Longyangxia hydropower station; sending hydropower and PV through common lines, compensation is not limited by the system grid structure and transmission capacity, etc., and promoting the consumption of new energy.

4.2. Analysis of the Impact on the Yellow River Water Scheduling and Downstream Terrace Power Generation. The PV power stations are mainly diurnal in nature and require intraday compensation from conventional power stations. In the hydro-PV combination power supply, the hydropower station compensates the PV power station mainly on an intraday basis. In the actual dispatching process, if the average power generation situation is used for dispatching, when the maximum power generation situation of the PV power station is encountered, the PV power generation output of hydro-PV complementary power combination increases and the hydropower output decreases, which requires the storage of water in the Longyangxia reservoir to reduce the output of the Longyangxia reservoir; in the case of minimum PV power generation, the PV power output of the hydro-PV complementary power combination decreases and the hydroelectric power output increases, requiring the release of water from the Longyangxia reservoir to increase the outflow of Longyangxia. According to the statistical analysis of the Longyangxia hydropower station from 1988 to 2010, with the change of water level in the Longyangxia reservoir, the water consumption per kWh is \(3.1 \text{ m}^3/\text{kWh} \sim 5 \text{ m}^3/\text{kWh}\). Based on an average water consumption of \(4 \text{ m}^3/\text{kWh}\) per kWh, it is estimated that the water output from the Longyangxia may be reduced by 970,000 m\(^3\) to 3.17 million m\(^3\) in the event of maximum PV generation; in the case of minimum PV power generation, the water volume out of the Longyangxia may increase by 2.02 million m\(^3\) \sim 4.64 million m\(^3\). The impact of the water output out of the Longyangxia hydropower is shown in Table 1.

After counter-regulation by the Laxiwa reservoir, the water output from Laxiwa is basically unchanged compared with that before the hydro-PV complementary supply, meeting the downstream gradient’s requirements for the water output from the Longyangxia reservoir. Therefore, the combined hydro-PV complementary power supply meets the requirements of the Yellow River water dispatch for the output of the Longyangxia hydropower station and has no impact on the Yellow River water dispatch and downstream gradient power generation.

5. Conclusions

This study constructs a mathematical model of hydro-PV power generation, analyzes the power output characteristics of hydropower and PV under different scenarios, discusses the hydro-PV complementary operation mode and the impact on the power grid under hydro-PV complementary, taking the actual power station of the Longyangxia as an example, and draws the following conclusions:

1. The high proportion of new energy sources connected to the power system has caused a significant increase in fluctuations in power generation. As power generation and supply are simultaneously completed in the power system, the grid operation must meet the power balance constraint and maintain the real-time balance of power generation and supply.

2. For the characteristics of PV power generation and hydroelectric power generation, the output of PV power units and hydropower units under different conditions are separately modeled considering the influence of weather and seasonal factors. It is found that PV power generation is affected by diurnal variation, weather variation, and moving clouds, and there are intermittency and fluctuation, while hydropower generation output is more stable.

3. Taking the hydro-PV power generation system at Longyangxia as an example, the hydro-PV complementary system was simulated under different scenarios, confirming that hydropower is a good complementary resource for PV power generation, which not only improves the quality of the grid but also enhances the capacity of new energy consumption.

4. Through the construction of the Longyangxia hydro-PV complementary project, the annual utilization hours of the Longyangxia hydropower station transmission line can improve the economic benefits of the power grid.

Therefore, the research on the impact of the operation of hydro-PV complementary systems on power grids based on new energy consumption can not only solve the urgent problems of practical projects but also play an important reference role for subsequent projects. The application and promotion of the research results will certainly play a positive role in promoting the development or revision of future industry or national codes, thus bringing huge social benefits.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.
Conflicts of Interest

The authors declare that they have no conflicts of interest.

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