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# Study on Benefit Evaluation System for Optimal Power Generation Dispatching of the Cascade Hydropower Stations

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***Abstract:***

Standardized evaluation of the hydropower station is an important content of the operation management for hydropower stations. This paper puts forward a set of relatively complete evaluation index system in terms of power generation, including power generation completion rate, improvement rate for power generation completion, and so on. Among them, the improvement rate for power generation completion shows the rise and fall degree of cascade power generation level in the river basin in the current year through longitudinal comparison of the cascade reservoirs' power generation completion rate in the current year and many years. The whole set of system can carry on quantitative calculation and qualitative description for each index, and carry out comprehensive evaluation of multi-objective optimal operation benefit of the cascade reservoirs. The cascade hydropower stations' theoretical generating capacity, power generation completion rate and improvement rate for power generation completion are calculated by examples. The results show that the optimal power generation dispatching level of the cascade hydropower stations is excellent. In conclusion, the benefit evaluation system of the cascade hydropower station is scientific and reasonable, which can provide reference for relevant research at home and abroad, and it has great theoretical significance and engineering practice value.

***Keywords:*** *Hydropower station, Evaluation system, Optimal operation, Power generation benefit*

## I. INTRODUCTION

The purpose of benefit evaluation system for dispatching is to select appropriate dispatching mode to make full use of water resources, which can not only judge the operation result of the dispatching mode to provide guidance for dispatching operation, but also mobilize the enthusiasm of hydropower station to strengthen technology and make great efforts to innovate, so as to achieve the purpose of improving water resource utilization efficiency.

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There are three emphases on the establishment of benefit evaluation system for dispatching: (1) Innovation model/algorithm. Such methods are evaluated by establishing the optimal dispatching model and using the calculated optimal solution as the reference value of traditional indexes. There are three ways to build such systems: One is based on changing the objective function of optimal dispatching or adding new constraints, the second is to calculate the optimal solution by using new algorithm, and the third is to mix the first two ideas for research. However, the traditional evaluation indexes are used in the evaluation. (2) Constructing new indicators. Based on the analysis of reservoir dispatching characteristics and deep understanding of traditional methods, a new evaluation index is put forward. There are three ways of thinking: One is to put forward the improved new index on the basis of the traditional index, the second is to use the evaluation index of other research fields into the research after improvement, and the third is to put forward the scientific and reasonable new index directly. (3) Proposing new evaluation methods. In the process of system establishment, it is necessary to fully consider how to ensure the indicators have sufficient representativeness, technical feasibility, scientific management and sustainable development. Only in this way can a scientific and feasible evaluation system be formulated, so that the significance of benefit evaluation can be truly brought into play.

Countries all over the world attach great importance to the standardization evaluation of the electric power industry. European and American countries have set up organizations for benchmarking management, which are responsible for benchmarking of electric power and energy industries, and most power main bodies are covered [1,2]. GG Dranka et al improved the calculation method of long-term average cost of energy saving for the power system with high renewable energy (including high proportion of hydropower) in Brazil. The results show that the investment for improving energy system efficiency can effectively save costs, reduce newly-installed capacity investment and reduce carbon dioxide ($CO_2$) emission in the long run, and the research provides reference for formulating energy development policies in this region [3]. At present, the research on benchmarking management abroad mainly improves and innovates the analysis method, benchmarking management model and benchmark evaluation index. Generally, the data envelopment analysis method is used to identify the relative effectiveness of different indicators, and the evaluation dimension is relatively macroscopic, mainly from the perspective of regional power distribution, with little research on single enterprise and even power plant [4].

In China, scholars focused on annual regulating power station or runoff power station at the beginning of the research, but the research on multi-year regulating power station was relatively scarce. In 2002, Liu Junping and Huang Qiang studied the cascade joint dispatching of the upper Yellow River and put forward a method of converting reservoir water into electricity for multi-year regulating reservoir. The checked electric quantity is the sum of the electric quantity contained in the calculated electric quantity and the stored water volume [5]. In 2006, Liu Zhao and Huang Qiang established the incremental assessment system for water saving of Gongboxia Hydropower Station with relative power generation water consumption rate and relative water energy utilization rate as assessment indicators [6]. In the same year, Chang Jianxia and Wang Yimin established the operation assessment model of hydropower station at the upper Yellow River based on the above indicators [7]. In 2007, Bai Xiaoyong et al introduced the assessment method for water-saving incremental dispatching of cascade hydropower stations in the upper

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Yellow River [8]. In the same year, Sun Desuo et al put forward the ratio of empty consumption on the basis of available water, and summarized the method for saving water and increasing power generation of the hydropower station [9]. In 2008, Cao Guangjing and Cai Zhiguo proposed the concept of\ "Power generation completion rate\", conducted preliminary exploration on the new theoretical method based on this concept, and developed the power generation benefit evaluation system of cascade hydropower stations [10]. In 2009, Zhang Junliang, Ma Guangwen et al established a set of quantitative and qualitative index system for the cascade reservoirs in the basin [11]. Cai Zhiguo and Cao Guangjing put forward a new idea aimed at optimizing potential tapping in 2011, and preliminarily established a new evaluation method for cascade hydropower stations by adopting the coupled model of fine simulation and optimal dispatching [12]. In the same year, Huang Weibin and Ma Guangwen et al realized systematic research and completed the development and design by using software programming and database technology, constructing the intelligent evaluation system of energy-saving dispatching benefit of cascade hydropower stations based on the benefit evaluation algorithm of United Nations CDM Executive Council [13].

In addition to the study on the benefit evaluation of the reservoir power generation, many scholars have also carried out researches on other utilization tasks. Liu Zhao, Xi Qiuyi et al proposed a set of evaluation system of water quantity index in 2014, and proposed flood resource accumulation rate and increase rate for flood resource accumulation to measure flood utilization degree of the hydropower station [14]. In 2015, Zhu Jiazhen and Wang Songlin adopted variation range method to study 5 sets of hydrological indexes including monthly average discharge, annual extreme discharge time and other 5 groups of hydrological indicators on cascade reservoirs in Wuxi River Basin. The results show that variation range method can effectively evaluate and reservoir diapatching will have impact on river ecology [15].

## II. EVALUATION INDEX SYSTEM OF POWER GENERATION DISPATCHING

In principle, the assessment & evaluation of hydropower station's power generation dispatching is to evaluate the influence of casting aside external uncontrollable factors (such as inflow runoff and power load), and only depends on the utilization degree of hydropower resources by dispatching mode. Since the water consumption rate for power generation, the improvement rate for water energy utilization, etc. are affected by the performance of hydraulic structures and electromechanical equipment, these parameters cannot be changed easily after the completion of the hydropower station, so relevant indexes are not adopted in this evaluation. Finally, power generation completion rate and improvement rate for power generation completion are selected as assessment indicators.

The conventional assessment idea is to carry out according to the dispatching diagram, which is often compared with the previous results. Certain evaluation effect can be achieved, but due to the difference of incoming water conditions each year, it is easy to be biased if the power generation in the year of relatively dry water supply is compared with that in the year of abundant inflow in the future. Therefore, the water condition should be excluded from the evaluation as far as possible, but in any case it will inevitably have an impact on the diapatching results, so its impact on the evaluation can only be minimized as far as possible. The idea of optimal dispatching evaluation is to output theoretical power generation according to certain constraint conditions and dispatching mode, taking the year’s given incoming water as input. The

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theoretical power generation at this point is no longer an absolute value, which will vary with decision preferences. Therefore, the connotation of theoretical power generation is convenient for different power stations to set the assessment benchmark meeting their dispatching requirements and actual conditions.

Taking the theoretical power generation as the evaluation benchmark, the power generation completion rate is a comparison between actual value and theoretical value, but it is not the only standard to judge the dispatching mode by its size alone. Up to 95% does not necessarily mean that the dispatching level is good, and the dispatching level at 85% is not inferior. For example, the completion rate of the power station's power generation is above 95% throughout the year and suddenly drops to 90%. Looking at 90% alone, it will be considered that the utilization rate of water resources is relatively high, but compared with many years, it will be found that it has actually decreased, which does not conform to the development concept of water saving and increasing generation. Therefore, the indicator value of the power generation completion rate obtained in a certain year should be compared with the index value for consecutive years, so as to see whether the dispatching mode of the power station in that year is improved compared with that before.

Finally, according to the solution, the theoretical generating capacity is obtained, and the index of power generation completion rate is calculated. For longitudinal comparison, the index of improvement rate for power generation completion is put forward.

2.1 Theoretical Power Generation

The theoretical generating capacity can reflect the hydropower station's generation potential, and its value is calculated according to different rules (dispatching diagram/dispatching model), and the calculation formula is shown in formula (1).

$$E_{i,b,t} = \sum^{t}(k_i Q_{i,t} H_{i,t})t \tag{1}$$

In this formula, $E_{i,b,t}$ is the theoretical generating capacity of the power station $i$ in the cascade hydropower station at the time period $t$; $k_i$ is the output coefficient of the power station $i$; $Q_{i,t}$ is the power generation flow in the the power station $i$ at the time period $t$; and $H_{i,t}$ is the upstream and downstream head difference within the time period $t$ of the power station $i$.

2.2 Power Generation Completion Rate

The power generation completion rate can measure the completion level of actual power generation compared with theoretical energy generation of the hydropower station. Its value is the ratio of actual power generation to theoretical energy generation, and the calculation formula is shown in formula (2).

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$$\alpha_{n,t}=\frac{\sum_{i=1}^{n}E_{i,t}}{\sum_{i=1}^{n}E_{i,b,t}}\times 100\% \tag{2}$$

In this formula, $E_{i,t}$ is the actual generating capacity of the power station $i$ in the cascade hydropower station at the time period $t$. $\alpha_{n,t}$ is the power generation completion rate of the cascade hydropower station(s); $n$ refers to the calculated number of cascade hydropower stations, and when calculating the power generation completion rate of the single station, the value of n should be 1.

Because the hydrological process has periodicity, e.g., the variation of a river's water quantity has rich and dry periods within a year; the process of annual water yield change is similar, though the annual total water volume is different. Generally, the river has a period of one year, so it is recommended that the annual cycle unit is adopted for evaluating power generation completion rate.

The installation, service time and maintenance input of hydraulic structures and electromechanical equipment of different power stations are different, so the scope of this indicator is different. Since the assessment and evaluation are for better dispatching, they should neither aim too far nor get too far away. Each power station should adjust the index range and evaluation requirements after comprehensive consideration of its actual situation to ensure that the power station can effectively improve the dispatching management level and make continuous progress under such specifications, so that the assessment can do well. Therefore, evaluation grade range of indicators of different power stations can be reasonably adjusted to conform to the reality of assessing power station.

2.3 Improvement Rate for Power Generation Completion

The improvement rate for power generation completion can reflect the rise and fall degree of the power generation completion level in the current year compared with the previous one. Its value is the relative difference between the power generation completion rate and the average power generation completion rate. The calculation formula is shown in formula (3).

$$\alpha_{up}=\frac{\alpha_{n,t}-\overline{\alpha}}{\overline{\alpha}}\times 100\% \tag{3}$$

In the formula,

$$\overline{\alpha}=\frac{\sum_{t=T-x}^{T-1}\alpha_{n,t}-Max(\alpha_{n,t})-Min(\alpha_{n,t})}{x-2}\times 100\% \tag{4}$$

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$\overline{\alpha}$ is the power station's average power generation completion rate of the previous $x$ time periods $t$ at the time period $t$ (If the data $x$ is less than 5 years, the maximum and minimum values need not be removed); $Max(\alpha_{n,t})$ is the maximum value of the power generation completion rate at the previous $x$ time periods $t$; $Min(\alpha_{n,t})$ is the minimum value of the power generation completion rate at the previous $x$ time periods $t$; If a single station is solved, the value of n should be 1.

If the value of $\alpha_{up}$ is negative, it indicates that the level of power generation completion rate in this year is lower than the average level of previous years, while the positive value of $\alpha_{up}$ indicates that this year's dispatching level has been improved.

The improvement rate for power generation completion is a multi-year comparison value, which is meaningful only with reference and comparison of previous data and it is normal that the value fluctuates slightly every year. It should be pointed out that the improvement rate of power generation completion at different power stations is difficult to reach a certain fixed value or above, so it is very likely that setting too-high grade score is meaningless. This paper only provides an assessment idea, and the specific implementation requires each power station to make its own adjustment according to the actual situation.

## III. MATHEMATICAL MODEL ESTABLISHMENT

### 3.1 Objective Function

The research object is a regulating reservoir. Given the inflow runoff sequence of the reservoir, the selected goal is to maximize the power generation under the given dispatching rules and satisfying the constraint conditions [16].

$$E = Max\sum_{t=1}^{T}(A \cdot Q_t \cdot H_t \cdot M_t) \tag{5}$$

In this formula: $E$ - Power station's power generation;

$A$ - Comprehensive output coefficient of the power station;

$Q_t$ - Power station's power generation flow during the time period $t$ ($m^3$/s);

$H_t$ - Average net head of the power station's power generation during the time period $t$ (m);

$M_t$ - Number of hours during the time period $t$;

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### 3.2 Constraints

#### 3.2.1 Water balance constraint

$$V_{t+1} = V_t + (q_t - Q_t - S_t)\Delta t \qquad \forall t \in T \tag{6}$$

In the formula: $V_{t+1}$ - Power station's reservoir storage capacity at the end of the time period $t$ ($m^3$);

$V_t$ - Power station's reservoir storage capacity at the beginning of the time period $t$ ($m^3$);

$q_t$ - Power station's intake flow ($m^3$/s) in the time period $t$;

$S_t$ - power station's abandoned water flow ($m^3$/s) during the time period $t$;

$\Delta t$ - length of the calculated period(s).

#### 3.2.2 Constraint of reservoir storage capacity

$$V_{t,min} \le V_t \le V_{t,max} \qquad \forall t \in T \tag{7}$$

In this formula: $V_{t,min}$ - The power station's minimum water storage capacity of the reservoir ($m^3$) that should be guaranteed during the time period t;

$V_t$ - Power station's reservoir storage capacity during the time period t ($m^3$);

$V_{t,max}$ - power station's maximum allowable reservoir storage capacity ($m^3$, usually based on reservoir safety considerations, such as the storage capacity corresponding to normal high water level of the reservoir, etc.) during the time period $t$.

#### 3.2.3 Constraint of reservoir letdown flow

$$Q_{t,min} \le Q_t \le Q_{t,max} \qquad \forall t \in T \tag{8}$$

In this formula: $Q_{t,min}$ - the power station's minimum letdown flow rate ($m^3$/s) that should be guaranteed during the time period $t$;

$Q_{t,max}$ - The power station's maximum allowable letdown flow rate ($m^3$/s) during the time period $t$.

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3.2.4 Constraint of power station output

$$N_{min} \le A \cdot Q_t \cdot H_t \le N_{max} \quad \forall t \in T \tag{9}$$

In this formula: $N_{min}$ - the power station's allowable minimum output (MW, depending on the type and characteristics of the turbine);

$N_{max}$ - Installed capacity of the power station (MW).

3.2.5 Non-negative conditional constraint

All of these variables above are non-negative (≥ 0).

## IV. CALCULATION EXAMPLE

Taking a cascade hydropower station as the research object, the actual dispatching situation of reservoir group in 2021 is evaluated. Power station A is located in the upstream of Power station B, power station A has seasonal regulation performance, power station B is the runoff-type power station, the joint operation of the two power stations has better dispatching performance. The characteristic values of power stations A and B are shown in TABLE I.

**TABLE I. Characteristic parameters of the power station**

| Power station | Maximum letdown flow rate ($m^3/s$) | Minimum letdown flow rate ($m^3/s$) | Output coefficient K | Head loss (m) | Design head (m) |
|---|---|---|---|---|---|
| A | 692 | 0 | 8.7 | 0.1 | 119 |
| B | 1096 | 0 | 8.9 | 0.1 | 62～88 |

According to the actual inflow conditions of Hydropower Station A in the current year, the dispatching mode of equal water level difference method in flood season (May to October) and equal output method (minimum output maximum) in dry season (November to April) is adopted in theoretical calculation. Power station B is a run-of-river reservoir, and its inflow flow is the sum of the discharge flow and the inflow in the section of power station A. Under the condition that the safety standard specified by the reservoir is not exceeded, the amount of incoming water determines the power generation.

The calculated generation process of A-B cascade theory is summarized as a table. See TABLES II and III for details."

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**TABLE II. Theoretical calculation of power station a's power generation process in 2021**

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Q | 302.2 | 291.3 | 305.5 | 343.8 | 469.8 | 439.4 | 358.8 | 367.4 | 243.2 | 237.7 | 280.2 | 310.7 |
| Zdc | 841.0 | 841.0 | 840.9 | 841.1 | 841.4 | 842.3 | 842.1 | 841.5 | 841.6 | 840.5 | 840.5 | 840.8 |
| Zdm | 841.0 | 840.9 | 841.1 | 841.4 | 842.3 | 842.1 | 841.5 | 841.6 | 840.5 | 840.5 | 840.8 | 841.0 |
| $\overline{Zd}$ | 841.0 | 841.0 | 841.0 | 841.2 | 841.8 | 842.2 | 841.8 | 841.5 | 841.0 | 840.5 | 840.7 | 840.9 |
| H | 117.7 | 122.2 | 116.3 | 103.3 | 96.90 | 102.2 | 108.3 | 114.2 | 120.4 | 126.6 | 126.8 | 117.8 |
| N | 30.91 | 30.96 | 30.91 | 30.91 | 39.60 | 39.06 | 33.79 | 36.50 | 25.46 | 26.18 | 30.91 | 30.91 |
| E | 2.258 | 2.262 | 2.258 | 2.258 | 2.89 | 2.85 | 2.47 | 2.67 | 1.86 | 1.91 | 2.26 | 2.26 |

**TABLE III. Theoretical calculation of power station b's power generation process in 2021**

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Qc, Up | 302.2 | 291.3 | 305.5 | 343.8 | 469.8 | 439.4 | 358.8 | 367.4 | 243.2 | 237.7 | 280.2 | 310.7 |
| Q interval | 47.87 | 49.35 | 30.97 | 66.13 | 134.2 | 72.84 | 76.64 | 48.07 | 8.47 | 8.3 | 11.06 | 32.30 |
| Qr | 350.1 | 340.7 | 336.5 | 410.0 | 604.0 | 512.2 | 435.4 | 415.4 | 251.7 | 246.0 | 291.2 | 333.3 |
| H | 87% Hmax constant head calculation | | | | | | | | | | | |
| N | 21.97 | 21.37 | 21.11 | 25.72 | 37.90 | 32.14 | 27.32 | 26.07 | 15.79 | 15.43 | 18.27 | 20.91 |
| E | 1.60 | 1.56 | 1.54 | 1.87 | 2.77 | 2.35 | 2.00 | 1.90 | 1.15 | 1.13 | 1.33 | 1.53 |

Note: In the above table, Zc refers to the initial water level of the upstream period, Zm refers to the end water level of the upstream period, $\overline{Z}$ is the average water level of the upstream period, Vc refers to the initial storage capacity of the upstream period, Vm refers to the end storage capacity of the upstream period, Q refers to the power generation flow, Zdc refers to the initial water level of the downstream period, Zdm refers to the end water level of the downstream period, $\overline{Zd}$ refers to the average water level in the downstream period, H refers to the head difference, N refers to the period output value, and E refers to the interval power generation. Water level unit is m, storage capacity unit is billion m3, flow unit is m3/s, output unit is 10,000 kW, and power generation unit is hundred million kW·h.

See Figures 1 and 2 for the output of A and B.

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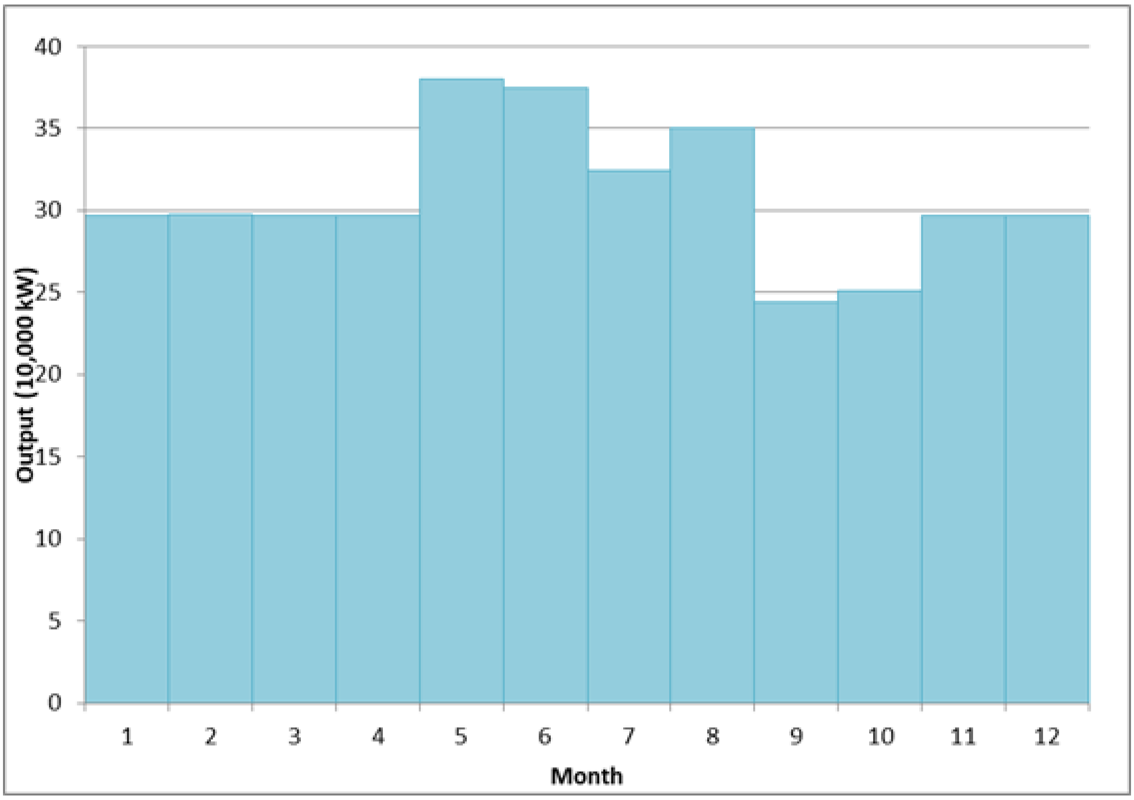


Figure 1: Calculation Theoretical Output Diagram of the Power Station A in 2021

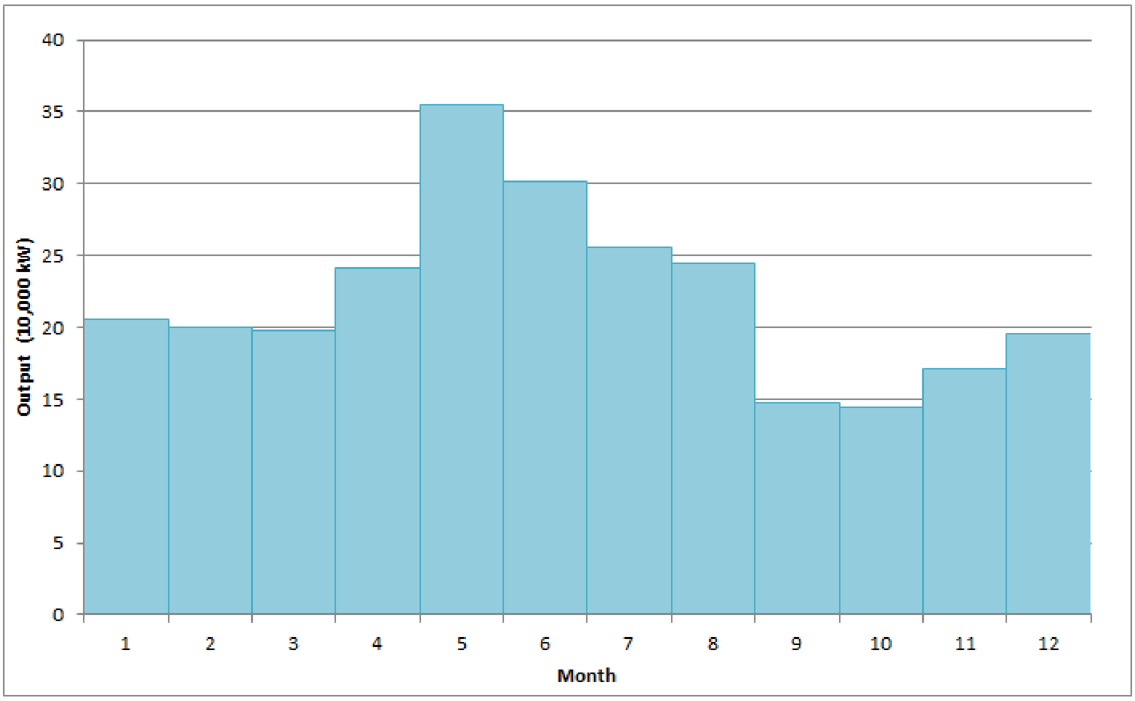


Figure 2: Calculation Theoretical Output Diagram of the Power Station B in 2021

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4.1 Power Generartion Completion Rate

The obtained results are calculated according to the formula, and the completion rate of A-B cascade power generation in 2021 can be obtained based on the score of single index. See TABLE IV for details.

**TABLE IV. Final score of the power generation completion rate of cascade reservoirs in 2009**

| Power station | Theoretical power generation | Actual power generation | Power generation completion rate $\alpha_{nt}$ ($\alpha_{i,t}$) |
|---|---|---|---|
| A | 28.206 | 26.86 | 95.2% |
| B | 20.746 | 19.22 | 92.6% |
| Step | 48.952 | 46.08 | 94.1% |

4.2 Improvement Rate for Power Generation Completion

According to the actual situation of power stations A and B, 2019 and 2020 are finally selected as the comparison periods of power generation completion rate in 2021, and the improvement rate for power generation completion is calculated. The calculation results of power generation completion rate of the two stations from 2019 to 2020 are shown in TABLE V.

It is calculated according to the formula:

Average power generation completion rate $\overline{\alpha}$ from 2019 to 2020 is (90.6%+93.5%)/2=92.05%

The improvement rate for power generation completion in 2021 - $\alpha_{up}=\frac{\alpha_n-\overline{\alpha}}{\overline{\alpha}}\times 100\%$ =(94.1%-92.05%)/92.05%=2.2%

**TABLE V. Final score of the power generation completion rate of cascade reservoirs from 2019 to 2020**

| Year | Power station | Theoretical power generation | Actual power generation | Power generation completion rate $\alpha_{nt}$ ($\alpha_{i,t}$) |
|---|---|---|---|---|
| 2019 | A | 25.75 | 23.52 | 91.3% |
| | B | 18.90 | 16.93 | 89.6% |
| | Step | 44.65 | 40.45 | 90.6% |
| 2020 | A | 31.14 | 29.63 | 95.2% |
| | B | 23.15 | 21.15 | 91.4% |
| | Step | 54.29 | 50.78 | 93.5% |

## V. CONCLUSION

The hydropower station’s development of \ "river basin, cascade, synthesis and rolling\" has become the development trend. The combined optimal dispatching of cascade hydropower stations in the basin is beneficial to improve the comprehensive utilization efficiency of water resources, and relieve the pressure of energy resources and environmental protection. It is necessary to establish a set of scientific and reasonable benefit evaluation system for cascade hydropower stations in order to better evaluate the management of hydropower station dispatching, identify the main problems of hydropower station’s actual dispatching, improve the management level of optimal operation of reservoir group, and fully promote the comprehensive utilization efficiency of water resources.

Therefore, this paper has carried on the thorough research around the evaluation system, constructed the evaluation index of the reservoir group,’s power dispatching benefit, and put forward a set of relatively complete evaluation index system from the aspect of power generation, on the basis of analyzing the influence factors of the reservoir dispatching benefit. Clarify the meaning, calculation formula and evaluation grade of each indicator, so that the indicators can be both quantitatively calculated and qualitatively described, and special cases should be explained.

Through the calculation of dispatching cases, the power generation completion rate and improvement rate for power generation completion are calculated. The evaluation results show that the multi-objective optimal dispatching level of Dongsuo cascade is excellent, and the satisfaction degree of generation completion rate and improvement rate for power generation completion is positively evaluated, and it is consistent with the actual situation, which verifies the scientific rationality of the evaluation system.

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