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# Profitability improvement of a reservoir power station based on virtual reservoir bidding

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## Abstract

Compared with a run-of-river power station, a reservoir power station (RPS), with the capacity of a seasonal regulation function and more, has the unique and irreplaceable attributes of its role in the power grid and society at large. However, under the current power system and market environment in China, these attributes cannot be effectively utilised, resulting in heavy losses to enterprises. It is inevitable for RPSs to participate in the market; therefore, how to improve the profitability of RPS enterprises has become an urgent problem requiring a solution. Based on the control effect on run-off of RPS in a river basin, a new cascade hydropower bidding method and the associated bidding process are proposed. The market entities of the new bidding method are composed of cascade hydropower joints with the RPS as the boundary. The bidding unit benefit-sharing mechanism is constructed, and the accounting method for the benefit-sharing price of the RPS is established, which finally achieves the goal of improving the profitability of the RPS enterprise.

*Keywords:* Benefit-sharing; Bidding; Power market; Profitability; Reservoir power station; Virtual reservoir

## Highlights

- The concept of a virtual reservoir is proposed for the first time, and the bidding process is designed.
- Combined with the benefit of the storage capacity of the RPS, a reservoir capacity method that takes into account the actual reservoir water level and the grid absorption rate is established to verify the contribution of the RPS to the bidding benefit.

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## 1. Introduction

### 1.1. Background and significance

A reservoir power station (RPS) not only plays a role in power generation and flood control but also has some benefits in navigation and water supply. Nowadays, in the context of the new power system reform and market environment of China, wind power and photovoltaic power generation implement the full purchase policy of 'quantity and insured price', while the RPS implements the 'plan + market' dual-track policy together with the run-of-river power station (ROR-PS). That is, the electricity is divided into planned electricity and market electricity, which are priced by government and by competition, respectively. However, compared with the ROR-PS, the cost of a RPS is always much higher due to its higher immigrant investment caused by a wider flooding area and a longer construction period. The RPS is at a more disadvantaged position than the ROR-PS under the non-differentiated market rules, and the sales revenue of RPS enterprises comes down every year as a consequence. In addition, with the gradual liberalisation of the power generation plan, the amount of planned electricity is decreasing annually, resulting in heavy losses to enterprises. The asymmetry of high cost and low income reduces the enthusiasm of enterprises to build the RPS, which will affect the high-quality development of the power industry. Therefore, research into methods and means to improve the profitability of RPS enterprises has theoretical significance and a practical value in improving the enthusiasm of enterprises to build the RPS and promoting the effective and reasonable development of water resources in river basins. Besides, it is beneficial to power supply structure improvement and water surplus management.

### 1.2. Literature review

Profitability is the ability of an enterprise to obtain profits, which is generally expressed as the amount of business profits and the level of business operations in a certain period of time. At present, the research into profitability improvement both in China and elsewhere mainly focuses on the evaluation and prediction of profitability for different types of enterprises, such as those involved in logistics (Cheng, 2010), electricity (Gomez-Quiles & Gil, 2012), banks (Bucevska & Misheva, 2017), and cars (Chavez & Sharma, 2018): such work resulted in the proposal of more macro-measures, placing more emphasis on management. Few scholars pay attention to the profitability improvement of hydropower enterprises. Helseth *et al.* analysed the operational profitability of a hydropower system selling both energy and reserve capacity in a competitive market setting, showing that how the power plant operation changes and profitability increases when considering the sale of reserve capacity (Helseth *et al.*, 2017). The primary contribution of other work (Akcay *et al.*, 2017) lay in the creation of a method that allowed investors to assess the profitability of a hydropower investment using a stochastic approach. Based on a global and transparent process regarding the reliability and economic criteria associated with alternatives, Medjoudj *et al.* (2012) developed a novel strategy for profitability evaluation, highlighting technical and organisational measures taken by the enterprise. Cai (2013) proposed a method to reduce the break-even point of hydropower stations and improve the profitability of enterprises. Taking a hydropower station in the Tibetan area of Sichuan as an example, Ma analysed the relationship between fiscal and taxation financial policies and the on-grid price of hydropower, based on which, some financial and taxation preferential policies were proposed to improve the competitiveness of hydropower prices (Ma, 2017). Combined with the characteristics of small hydropower, Zhou & Liu (2006) gave suggestions for improving the competitiveness thereof. Liu *et al.* (2018) suggested fiscal, tax, and banking policies to improve the competitiveness and sustainability of the hydropower development in the Tibet and Sichuan-Yunnan Tibetan areas. We believe that the studies above have achieved good results in evaluating and predicting profitability, but the research on profitability improvement is not yet sufficiently deep. Combined with influencing factors, other workers always propose more macro-management suggestions.

The word 'virtual' refers to a new type of information interaction that does not exist in a traditional material form. In recent years, the appearance of words, such as 'virtual power plant (VPP)', 'virtual water network' (Selim & Abdalbaki, 2019), and 'virtual water trade' (Hassan & Thiam, 2015), has proposed new ideas for solving water resource management issues. Referring to the above research, this paper proposes a benefit-sharing mechanism based on 'virtual reservoir (VR)' bidding. The main contributions of this work are as follows: (1) with reference to the idea of a VPP, and based on the complex hydrologic, hydraulic, and electric connections between the upstream and downstream reaches of the cascade, the concept of a VR is proposed for the first time and the bidding process is designed and (2) combined with the benefit of the storage capacity of the RPS, a method that takes into account the actual reservoir water level and the grid absorption rate is established to verify the contribution of the RPS to the bidding benefit.

## 2. Attributes of the RPS

### *2.1. Run-off regulation*

There are strong coupled hydraulic connections between the stations in the upstream and downstream reaches, and thus, the completion of a hydropower station has changed the run-off distribution across the whole river basin. The operation mode, storing water in the flood season for use in the dry season, of the reservoir has reduced the imbalance in the run-off distribution during the year. And the huge storage capacity has a good regulation effect on water utilisation, run-off, and flood control in the basin, especially for large-scale control reservoirs. As the run-off regulation control centre for the river, the completion of the leading reservoir will have a significant effect on downstream stations' inflow process. For example, the Longyangxia Hydropower Station, the leading RPS in the upper reaches of the Yellow River, is a large-scale comprehensive utilisation pivot project with many years of regulating performance, whose regulating storage capacity is up to 19.4 billion $m^3$. After the Longyangxia Reservoir was put into operation in 1986, the regulating performance of the upper reaches of the Yellow River has been much improved, and the inflow process of the downstream station Liujiaxia has also undergone major changes (Wang *et al.*, 2017). The water storage period of the Yellow River Basin is from June to October annually, while the water supply period runs from November to May in the next year. As shown in Figure 1, influenced by the Longyangxia Reservoir, the ratio of the inflow of the Liujiaxia Reservoir during the water storage period to the supply period decreased from 2.36 to 1.03, and the inflow process line was flattened.

### *2.2. External benefits*

The RPS has many positive external benefits. Firstly, it will confer significant improvements to the environment (Ren *et al.*, 2018) after the completion of the reservoir. On the one hand, as a kind of clean

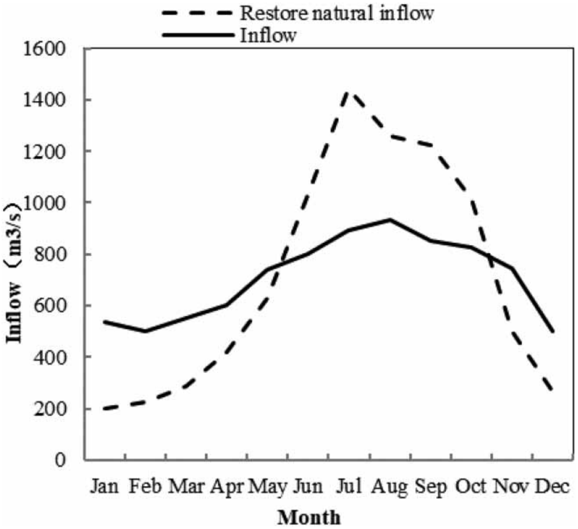


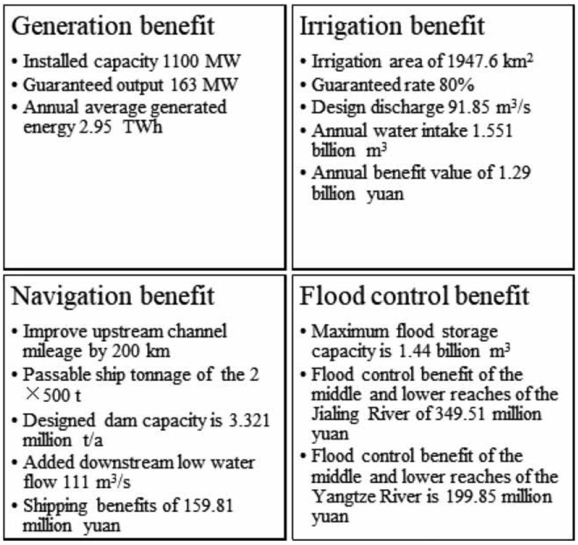
Fig. 1. The monthly inflow process of Liujiaxia Reservoir from 1987 to 2015.

energy, hydropower is very conducive to a reduction in fossil energy consumption and air pollution as well as global warming alleviation. On the other hand, the periodic water storage and release of the reservoir has a positive effect on local climate, terrestrial ecology, and water quality. For example, the power generation capacity of the Ertan Hydropower Station on the Yalong River can reach 17 TWh per year, which can reduce coal consumption, sulphur dioxide emission, coal-burning, and wastewater discharge by 6.3 million tons, 230,000 tons, 1.9 million tons, and 45 million tons per year, respectively, having significant benefits for improving energy structure and reducing emissions and waste. Secondly, the water conservancy tasks of large-scale reservoirs involve various aspects, whose comprehensive utilisation benefits are enormous. As shown in Figure 2, the Tingzikou Water Conservancy Project, as the only control project in the mainstream of Jialing River, has comprehensive benefits on power generation, flood control, irrigation, water supply, and shipping. Thirdly, the RPS can also stabilise the output random fluctuation of wind and photovoltaic power generation, which promotes new energy consumption (Lopes & Borges, 2015). Besides, with the development of power market, the RPS is of great importance to the efficient use of ROR-PS downstream to generate electricity as well as surplus water management. All in all, the RPS has an irreplaceable role in the power grid and society.

## 3. VR bidding

### 3.1. The connotation of a VR

To solve the defects of distributed energy, such as large quantity, low controllability, high grid connection cost, and difficult scheduling (Liang *et al.*, 2019), the concept of the VPP has been proposed. The VPP is a virtual control aggregation composed of distributed power sources, energy storage systems, and loads in an area, which can be reliably integrated into the grid and provide users with stable power (Baringo *et al.*, 2019).



**Generation benefit**

- Installed capacity 1100 MW
- Guaranteed output 163 MW
- Annual average generated energy 2.95 TWh

**Irrigation benefit**

- Irrigation area of 1947.6 km$^2$
- Guaranteed rate 80%
- Design discharge 91.85 m$^3$/s
- Annual water intake 1.551 billion m$^3$
- Annual benefit value of 1.29 billion yuan

**Navigation benefit**

- Improve upstream channel mileage by 200 km
- Passable ship tonnage of the 2 × 500 t
- Designed dam capacity is 3.321 million t/a
- Added downstream low water flow 111 m$^3$/s
- Shipping benefits of 159.81 million yuan

**Flood control benefit**

- Maximum flood storage capacity is 1.44 billion m$^3$
- Flood control benefit of the middle and lower reaches of the Jialing River of 349.51 million yuan
- Flood control benefit of the middle and lower reaches of the Yangtze River is 199.85 million yuan

Fig. 2. Benefits of the Tingzikou reservoir project.

Based on the idea of the VPP, we propose the concept of the VR: this refers to the integration of an RPS with its downstream ROR-PSs, where the regulation function of the RPS should be seasonal and more. A river basin can usually be divided into a number of VRs (see Figure 3). And power stations can participate in market competition and power dispatching in the form of a VR.

Similar to the VPP, a VR does not have an entity, and it pays more attention to the functions and effects of external presentation, but the two have obvious differences. Firstly, the plants that make up the VPP are independent, while there are mutually beneficial symbiotic relationships between the

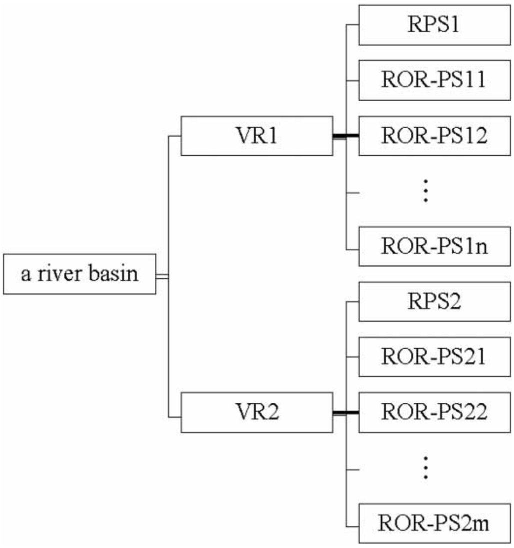


Fig. 3. The composition of a VR system.

plants in a VR. A VPP consists of distributed power sources in the region, including small hydropower, wind power, photovoltaic power, gas turbines, biogas power, and other scattered micro-power plants. Each power station is mutually independent but has the same problems of being small scale, suffering high cost of grid connection, low controllability, and difficulty in scheduling: these are the root causes of the emergence of VPPs. The power stations that make up the VR belong to the same river basin, with the strong coupling of electrical and hydraulic connections. The RPS in the upstream compensates the downstream station for run-off, and in turn, the station in the downstream redistributes the outflow of the upstream reservoir. In addition, the market mechanism of 'generate by contract, penalty for breach of contract' has increased the dependency of downstream ROR-PS on upstream RPS' run-off. Only when the stations in the river basin are coordinated and unified, can the collective and individual win–win status be realised, and the maximisation of interests is the fundamental driving force for the formation of the VR. Secondly, a VPP generally requires energy storage systems to regulate the output, while the reservoir in a VR can keep the output stable. The output of stations in a VPP always moves randomly, which cannot be completely solved by the bundling of power supply. Therefore, an energy storage system is needed to achieve the purpose of output control. VR is different: on the one hand, the output of a hydropower station is more stable than that of the new energy sources such as wind power and solar energy. On the other hand, as a natural energy storage system, the huge reservoir of the RPS can store electricity in the form of water. Thirdly, a VPP has the duality of power and load, while VR generally plays the role of generator. The VPP presents a wide-area spatial distribution, whose internal components often contain load(s): the VPP can be used as a power source to supply power to the grid, or as a load to absorb part of the power therefrom. The power of VR is generally connected to the main grid from the connection point and is supplied to the user.

### 3.2. Feasibility of VR bidding

In fact, VR bidding adopts the unified management mode of the river basin; therefore, it has a good theoretical basis, policy support, hardware facilities, technical support, and related experience (see Figure 4). The joint scheduling theory and the benefit-sharing method are the theoretical basis of VR

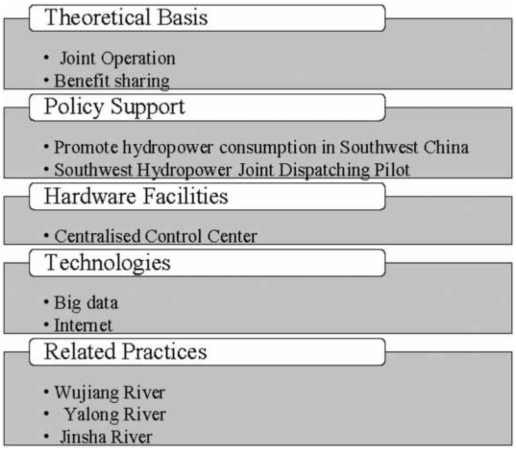


Fig. 4. The basis of the VR bidding framework.

bidding. The fundamental motivation for the formation of VR is to achieve multi-win. Therefore, a key premise of VR bidding is the sharing and rational allocation of benefits. In theory, the VR bidding method has a positive impact on its revenue, which is a necessary prerequisite for the formation of a VR. The second is the allocation of benefits: members of a VR can be divided into two categories according to their regulation performance, one is the RPS with a seasonal or better regulation function and the other is ROR-PS. Among them, the RPS exerts a controlling effect on the run-off, whose operation mode is the key to the benefit of VR; however, the maximisation of the benefits of RPS is often incompatible with that of VR. Therefore, under the VR bidding mode, the actual power sale revenue of RPS will inevitably suffer losses, while other power stations are obliged to compensate the RPS. Experts and scholars in the industry have carried out research on this issue, and the proposed benefit allocation methods mainly include three categories: single index method, comprehensive index method, and cooperative game method, which can be used as references herein.

VR bidding can not only increase power generation, improve overall revenue, but also help water surplus management. To promote hydropower consumption in the south-western region of China, state departments have issued policies allowing the implementation of pilot projects for hydropower joint dispatch. In response to a national call, and for management convenience, most river basins have built basin-wide centralised control centres based on big data and Internet technologies, providing good hardware facilities and technical conditions for VR bidding. The joint dispatch management practices of the Wujiang River, the Yalong River, and the Jinsha River also provide a reference for VR bidding.

In summary, VR bidding has a relatively mature soft and hard foundation and has a certain operability.

### *3.3. The process of VR market participation*

Similar to VPP bidding, VR bidding is a mode to participate in the market, in which cascade hydropower stations are bundled into a VR to achieve joint bidding and dispatch. As shown in Figure 5, the processes necessary for market participation are more complicated than other single-station bidding entities. VR bidding processes are mainly divided into two levels: the first layer describes the process of competition between a VR and other entities in the market, which is not different from a single-station bidding scenario; the internal management of the VR is mainly carried out on the second layer. Firstly, before participating in the market, each member needs to calculate its own generation capacity and cost, so as to form the total power generation capacity and comprehensive cost of the VR, in preparation for market bidding. Secondly, after successful bidding, the power dispatching centre will issue a production plan for the VR. Then, the power generation plan is distributed among the members, with the goal of maximising the resource utilisation or energy storage to achieve long-term benefits. Finally, after the completion of power generation, the grid will settle the on-grid electricity of VR according to the contract price, and the members will share the benefits.

The fundamental goal of the VR bidding method is to achieve multi-win outcomes. The complete process of VR bidding includes the formation of VR, strategic quotation, allocation of winning power, and bidding benefit verification and sharing. The strategic quotation is the core precondition for successful bidding, and the verification and sharing of bidding benefits is the key to maintaining the long-term stability of the VR. In view of this, we now examine the benefit-sharing mechanism.

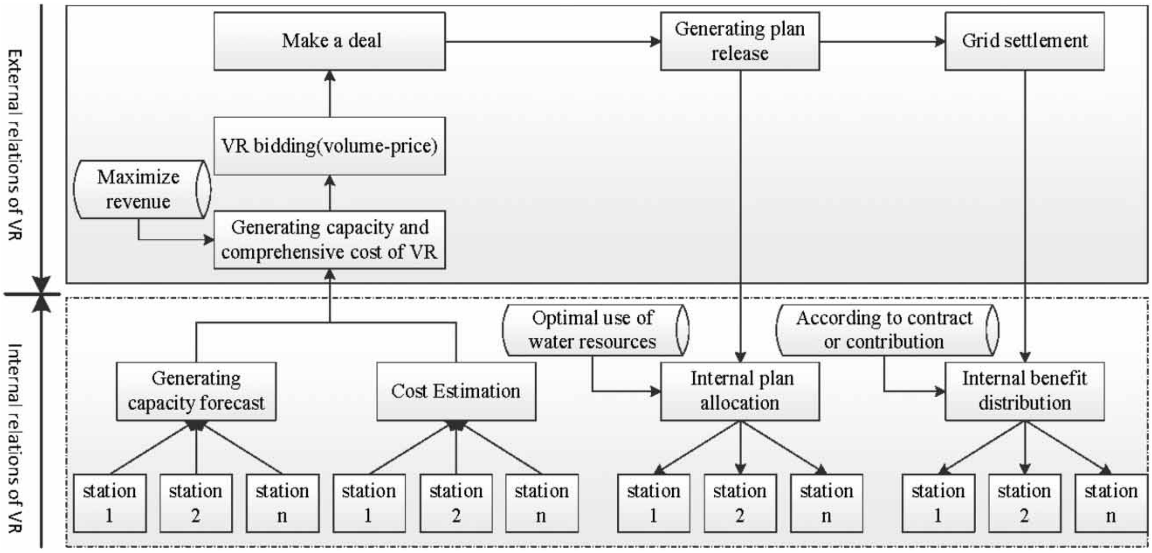


Fig. 5. Process of VR market participation.

In China, the value of 1 kWh electricity generated by RPSs and ROR-PSs is regarded as equivalent. So, we propose a VR bidding benefit-sharing mechanism to compensate for the external benefits of RPSs, which cannot be reflected in China's current electricity value system. However, it is not applicable to the well-developed foreign markets in which the value of electricity contains external values. For example, Japan proposes to divide the value of electricity into capacity value, kilowatt-hour value, balance service value, and other external values. The external benefit of the power station can be measured by the comprehensive electricity price, so the VR method is not suitable for the Japanese electricity market. But for other markets like China that only measure the value of electricity by kilowatt-hours, the VR method has universal applicability.

## 4. Benefit-sharing mechanism

The benefit-sharing mechanism defines the way for VR members to share the benefits created by the VR bidding method. As the run-off control centre of a VR, the RPS is the main contributor. So, we first study the method for RPS to share the benefit, and the sharing method for remaining stations is reserved for future research.

### *4.1. Benefit contribution verification method of the RPS*

The contribution of RPS to the downstream station mainly depends on the regulating storage capacity (the storage capacity between the normal water level and the dead water level) of the reservoir. The RPS can make full use of its storage capacity to store water in the flood season and discharge water during the dry season to generate electricity; therefore, in non-flood periods, in addition to the normal inflow to the basin, the inflow to the downstream stations has increased by the amount of water storage of the RPS.

That is, the contribution of RPS to the downstream station mainly refers to the amount of electricity corresponding to the storage capacity of the reservoir. In view of this, we proposed a new method for verifying the contribution of RPS to the VR bidding unit: the regulating storage capacity method.

Considering the water demand of the reservoir, such as irrigation and water supply, the regulating storage capacity method defines the contribution of an RPS to the VR bidding unit as the increased electricity benefit in the non-flood period due to the stored water in the reservoir. The flood season in Sichuan Province generally occurs in June to October, while the non-flood period generally refers to November to May in the next year. The benefit contribution of RPS to the ROR-PS in the regulating storage capacity method is calculated according to the following formula:

$$P_{\text{icom}} = \frac{V_r - W_d}{\delta_i} \times c_i \tag{1}$$

where $i$ is the station number, $P_{\text{icom}}$ is the contribution of RPS to station $i$ (¥), $V_r$ represents the regulating storage capacity of an RPS (m$^3$), $W_d$ represents the amount of water that needs to be drawn directly from the reservoir due to water demands such as irrigation and water supply in the non-flood period (m$^3$), $\delta_i$ is the average water consumption rate of station $i$ (m$^3$/kWh); and $c_i$ is the electricity price of station $i$ (¥/kWh).

The aforementioned method is an idealisation based on the premise of reservoir's full storage at the end of the flood season and power generation's full absorption by the power grid. The reality is different: for example, a multi-year regulation reservoir is not full at the end of the flood season in most years, or it is operated according to the annual regulating reservoir level. Run-off shows differences in abundance between years, and annual regulating reservoirs may not be able to store to the normal water level in dry years. In addition, in the current market environment of oversupply, the power grid cannot absorb all the power generation of the stations, so a comprehensive coefficient will be introduced here to improve the regulating storage capacity method:

$$P_{\text{icom}} = K_i \frac{V_r - W_d}{\delta_i} \times c_i \tag{2}$$

where $K_i$ is the comprehensive coefficient, mainly considering the impact of the actual water stored in a reservoir at the end of the flood season and the grid's absorption rate of the power generated. The meaning of other symbols is as described above. $K_i$ is calculated according to the following formula.

$$K_i = k_v \times k_{ai} \tag{3}$$

where $k_v$ is the ratio of reservoir's actual stored water to its regulating storage capacity, $k_{ai}$ is the grid's absorption rate of the power generated by station $i$, which is the ratio of on-grid electricity to theoretical power generation. The meaning of other symbols is as described above. The benefit contribution of RPS to the VR bidding unit is calculated according to the following formula:

$$P_{\text{com}} = \sum_{i=2}^{N} K_i \frac{V_r - W_d}{\delta_i} \times c_i \tag{4}$$

where $P_{\text{com}}$ is the total benefit contribution of RPS to the VR bidding unit (¥). The meaning of other symbols is as described above.

### 4.2. Benefit-sharing price of RPS

The benefit-sharing price of RPS refers to the equivalent price after sharing the bidding benefit, which is equal to the sum of the electricity price sold in the market and the sharing benefit per unit of electricity. After sharing the bidding benefits, the actual electricity price can be improved, which is conducive to the orderly participation of high-cost RPSs in market competition. The benefit-sharing price of RPS can be easily calculated according to the following formula:

$$C_{\text{com}} = (E_1 \times c_1 + \sum_{i=2}^{N} \alpha_i (P_{i\text{com}} - \text{Tax}_i)/E_1 \tag{5}$$

where $C_{\text{com}}$ is the benefit-sharing price excluding tax of RPS (¥), $P_{i\text{com}}$ is the benefit contribution of RPS to station $i$ (¥), $\text{Tax}_i$ is the circulation link tax and fee that shall be deducted from the benefit contribution of station $i$, $\alpha_i$ represents the benefit-sharing factor of station $i$, $c_1$ is the RPS's price (excluding tax) of electricity sold in the market (¥/kWh), and $E_1$ is actual power sales made by an RPS in the market (kWh).

## 5. Case study

### 5.1. Overview of VR Y

This section takes VR Y consisting of cascade hydropower stations in a river in Sichuan Province as an example to check the effectiveness of the VR bidding benefit-sharing mechanism on RPS gain.

We call the river included in this study River R. River R is the largest tributary of the Minjiang River, originating from the southern foot of Guoluo Mountain in Qinghai Province. The total length of its mainstream is 1,062 km, and the catchment area of the basin is 77,400 km$^2$. A total of 28 cascade hydropower stations, including three controlled reservoirs, are planned for mainstream operation on River R. The downstream controlled reservoir A has been put into operation in 2009, while the remaining two are still under construction. Therefore, Reservoir A is taken as a node, and the downstream section of River R forms the area of interest in this research.

Station A, the 19th of 28 hydropower stations, is a large-scale hydropower project that is mainly based on power generation and has comprehensive benefits such as flood control and sand interception. The control basin area of Station A is 68,512 km$^2$, accounting for 88.53% of the total basin area, and the average annual flow is 1,230 m$^3$/s. With a total installed capacity of 3,600 MW, Station A can generate almost 1.458 TWh of electricity per year. Having the capacity of a seasonal regulation function, the total storage capacity of Reservoir A is up to 5.39 billion m$^3$. Station A is the run-off control centre of the VR and the compensation object of the downstream stations.

A total of nine daily regulation (ROR) PSs, whose basic parameters are listed in Table 1, are planned below Station A. Relative positions of the 10 stations are illustrated in Figure 6. In addition to Stations G

Table 1. Basic parameters of the 10 stations planned in the downstream reach of River R.

| Station name | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| Control basin area (km$^2$) | 68,512 | 72,900 | 73,057 | 76,383 | 76,479 | 76,717 | 73,197 | 73,339 | 73,632 | 76,130 |
| Average annual flow (m$^3$/s) | 1,230 | 1,350 | 1,360 | 1,470 | 1,490 | 1,490 | 1,360 | 1,370 | 1,390 | 1,470 |
| Normal water level (m) | 850 | 660 | 624 | 474 | 432 | 398 | 592 | 578 | 554 | 528 |
| Regulating storage ($10^8$ m$^3$) | 38.82 | 0.08 | 0.435 | 0.55 | / | / | 0.015 | 0.0526 | 0.0585 | 0.87 |
| Total installed capacity (MW) | 3,600 | 660 | 720 | 700 | 480 | 772 | 246 | 330 | 348 | 770 |
| Annual power generation ($10^8$ kWh) | 145.8 | 31.89 | 32.90 | 29.56 | 24.07 | 32.93 | 12.19 | 15.34 | 16.10 | 34.178 |
| Guaranteed output (MW) | 926 | 107 | 206 | 131 | 151 | 204/98.1 | 83.76 | 122.6 | 124.5 | 179 |
| Total investment ($10^8$ ¥) | 169.42 | 52.58 | 87.87 | – | 27.82 | 77.14 | 50.75 | 61.39 | 44.22 | 48.9 |

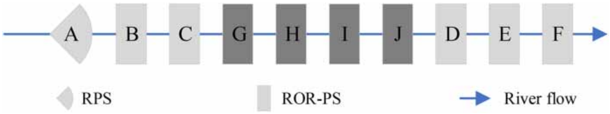


Fig. 6. Relative positions of the 10 stations.

and H, the other seven stations have been put into operation. We have no relevant information about Stations I and J, so the VR Y is here composed of six hydropower stations with a total installed capacity of 6,932 MW. Table 2 lists the parameters of each member of VR Y.

### 5.2. Data

According to the market participation flow in Figure 5, the members of VR Y form the total power generation capacity and comprehensive cost of the bidding unit after power generation capacity prediction and cost estimation on an individual basis, and participate in market as a bidding unit. Assume that the bidding unit's winning bid is E, and the bidding price is C (here, the winning electricity bid E takes the actual on-grid energy of VR Y in 2017): to ensure the power proportion between members of VR Y under resource optimisation configuration criteria, the actual on-grid energy of each member station is calculated according to formula (6). According to formula (7), the bid-winning electricity price is the

Table 2. Parameters of each member of 'VR Y'.

|  | Output threshold (MW) |  | Discharge threshold (m$^3$/s) |  | Level threshold (m) |  |  |
|---|---|---|---|---|---|---|---|
| Station name | Maximum | Minimum | Maximum | Minimum | Maximum | Minimum | Water consumption rate (m$^3$/kWh) |
| A | 3,600 | 500 | 2,772 | 327 | 850 | 790 | 2.68 |
| B | 660 | 110 | 2,619 | 327 | 660 | 655 | 12.39 |
| C | 720 | 0 | 2,697 | 327 | 624 | 618 | 12.5 |
| D | 700 | 20 | 2,225 | 345 | 474 | 469 | 12 |
| E | 480 | 0 | 2,203.2 | 373 | 432 | 429.95 | 15.95 |
| F | 772 | 0 | 2,640.45 | 300 | 398 | 397 | 11.69 |

product of the weighted electricity price of each station's designed power generation and the implementation rate of the average approved electricity price of Sichuan's hydropower output. The main calculation parameters are shown in Table 3.

$$\begin{cases} E = \sum_{i=A}^{F} E_{oi} \\ E_i = \dfrac{E_{fi}}{\sum_{i=A}^{F} E_{fi}} E \end{cases} \tag{6}$$

where $E$ is the bidding unit's quantity of winning electricity in the market (kWh), $E_i$ (kWh) is the production power allocated to station $i$, $E_{oi}$ is the actual on-grid energy in 2017 from station $i$ (kWh), and $E_{fi}$ is the average annual electricity at station $i$ under resource optimisation configuration criteria (kWh). The meaning of other symbols is as described above.

$$C = \frac{\sum_{i=A}^{F} E_{di} \times C_{ai}}{\sum_{i=A}^{F} E_{di}} \times \lambda \tag{7}$$

where $E_{di}$ is the design power output generated by station $i$ (kWh), $C_{ai}$ is the approved electricity price from station $i$ (¥/kWh), and $\lambda$ is the implementation rate of the average approved electricity price of Sichuan's hydropower output (74% in 2017). The meaning of other symbols is as described above.

To ensure the repeatability of the simulation, some notes pertaining to the data are made as follows: firstly, according to the regulating storage capacity method (formula (4)), the contribution of Reservoir A to other members of VR Y is calculated. Assume that Reservoir A is at full storage at the end of the flood season, that is, $k_v = 1$. The power absorption rate by the grid is the ratio of the actual on-grid power to the designed power generation in the current year. Although there are many types of taxes and fees to be paid during the operating period of such hydropower stations, including value-added tax, corporate income tax, large- and medium-sized reservoir area funds, water resources fees, and sales tax surcharges, from the analysis of the economic impact of the power station, the value-added tax has the greatest effect and the amount is also significant; therefore, the tax is mainly considered as being solely value-added tax, whose tax rate

Table 3. Main calculation parameters.

| Station name | $C_{ai}$ (¥/kWh) | $E_{oi}$ ($10^8$ kWh) | $E_{di}$ ($10^8$ kWh) | $E_{fi}$ ($10^8$ kWh) |
|---|---|---|---|---|
| A | 0.346 | 120.36 | 145.80 | 144.21 |
| B | 0.300 | 28.35 | 32.35 | 32.43 |
| G | 0.308 | 26.39 | 32.90 | 36.02 |
| H | 0.218 | 31.09 | 32.36 | 32.96 |
| I | 0.288 | 16.41 | 24.07 | 26.36 |
| G | 0.308 | 23.79 | 31.44 | 31.43 |

for hydropower generators in 2017 is 17%. Regarding the benefit-sharing coefficient of different stations, we take the same value for calculation convenience. In actual production operations, different power stations can take different values due to differing actual conditions, such as geographical location, distance from the RPS, and whether there is a tributary between them, or not.

### *5.3. Results*

According to formula (5) and the aforementioned calculation parameters, it is easy to get the benefit-sharing price of Station A when the benefit-sharing coefficient $\alpha_i$ takes different values. As shown in Table 4, when $\alpha_i$ varies from 0.1 to 0.8, Station A can obtain a unit power-sharing benefit of 0.0022–0.0174 ¥/kWh. This part of the benefit arises from the income of other members after deducting taxes and fees, so it can be regarded as the additional net income of the RPS. When the benefit-sharing coefficient reaches 0.8, Station A can receive an additional net income of 204 million ¥. Converting the unit electricity-sharing benefit into a tax-inclusive value, and superimposing it on the bid price, the equivalent electricity price and the approval electricity price implementation rate of A under the benefit-sharing mechanism can be obtained. Figure 7 illustrates the implementation rate, and the improvement of the approved electricity price after Station A shares the bidding benefit. It is obvious that the implementation

Table 4. Benefit-sharing price of RPS A.

| | | Unit power-sharing benefit (¥/kWh) | | | | |
|---|---|---|---|---|---|---|
| Number | Benefit-sharing coefficient | Excluding tax | Including tax | Bidding price (¥/kWh) | Benefit-sharing price (¥/kWh) | Implementation rate (%) |
| 1 | 0.1 | 0.0022 | 0.0026 | 0.2326 | 0.2351 | 67.96 |
| 2 | 0.2 | 0.0044 | 0.0051 | 0.2326 | 0.2377 | 68.70 |
| 3 | 0.3 | 0.0065 | 0.0077 | 0.2326 | 0.2402 | 69.44 |
| 4 | 0.4 | 0.0087 | 0.0102 | 0.2326 | 0.2428 | 70.17 |
| 5 | 0.5 | 0.0109 | 0.0128 | 0.2326 | 0.2454 | 70.91 |
| 6 | 0.6 | 0.0131 | 0.0153 | 0.2326 | 0.2479 | 71.65 |
| 7 | 0.7 | 0.0153 | 0.0179 | 0.2326 | 0.2505 | 72.39 |
| 8 | 0.8 | 0.0174 | 0.0204 | 0.2326 | 0.2530 | 73.12 |

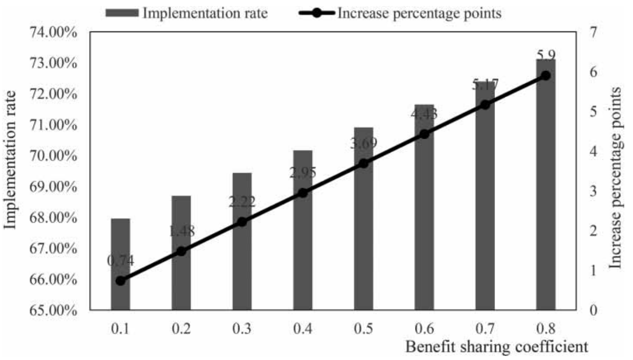


Fig. 7. The implementation rate and improvement of the approved electricity price after Station A share its bidding benefit.

rate of the approved electricity price has been improved. When the benefit-sharing coefficient is 0.8, the implementation rate can be increased by 5.90 percentage points, thus reaching 73.12%.

As mentioned above, there are a total of nine daily-regulated (run-of-the-river) power stations planned downstream from Station A: when all such stations are put into operation, a cascade development pattern of 'one reservoir and 10 levels' will be formed, and the scale of VR will be further increased as well as the beneficial contribution from Station A. Under the benefit-sharing mechanism proposed in this paper, RPS A will also generate a more substantial sharing benefit: its implementation rate of the approved electricity price will increase by nearly 10 percentage points. According to the way that sharing benefits from one station can increase the RPS' implementation rate by 1%, this will have a significant positive effect on improving the market competitiveness of Station A and stimulating its participation in market competition. It can be seen that the benefit-sharing mechanism based on VR bidding is an effective way to ensure the normal production and operation of an RPS, encourage its participation in the market, and promote the sustainable high-quality development of the hydropower industry. However, the determination of the benefit-sharing coefficient is the key to this policy.

## 6. Conclusion

Under the current spontaneous role of China's electricity market mechanism, the cost–benefit of power generation in the RPS is asymmetric, and its external benefits cannot be fully utilised, resulting in the market being unable to find the true value of RPS, and the energy allocation efficiency thereof is low. Vicious competition has caused enterprises to be overwhelmed. Excessive marketisation not only affects the normal production and operation of existing RPSs but also dampens the enthusiasm of enterprises towards investing in new RPSs. To ensure the normal production and operation of RPS enterprises and promote the high-quality development of the hydropower industry, we investigated the profitability improving method of RPS. The key conclusions are as follows.

Firstly, the VR bidding method based on the concept of VPP aggregation has relatively mature soft and hard foundations and has considerable operability.

Secondly, the regulating storage capacity method proposed here to verify the RPS's benefit to the VR bidding unit takes into account the effects of supply and demand situations and changes in run-off, which is better suited to the current market environment and more in line with reality.

Thirdly, according to the simulation results of VR Y, when the benefit-sharing coefficient is 0.8, the implementation rate of the approved electricity price of RPS A can be increased by 5.90 percentage points, which can significantly improve the electricity price.

Finally, a method of verifying the contribution of RPS excluding ROR-PS to the bidding unit is proposed. The determination of the benefit-sharing coefficient of each station and the effects of the bidding method on the bid price warrant further study.

Besides, the establishment of VR in this study mainly relies on run-off regulation between cascade reservoirs. Therefore, the profitability improvement method of parallel reservoirs without direct hydraulic connections needs further study.

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## Data availability statement

All relevant data are included in the paper or its Supplementary Information.

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