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Pricing of grid electricity of reservoir power plants based on quantification of the values of positive externality factors

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Abstract

Hydropower is a clean, low-carbon renewable energy source with the merits of mature technology and flexible operation. Moreover, hydropower plants provide comprehensive utilization functions in many areas, including flood control, shipping, and emission reduction. In the current contradictive situation between power supply and demand, China's hydropower grid pricing mechanism does not reflect the positive externality of hydropower, which is not conducive to fair competition between hydropower and other power sources. This study proposed the concept of the positive external electricity price (PEEP) and a pricing mechanism that considered, for the first time, the values of hydropower positive externality factors by using the positive externality theory. A representative quasi-public welfare power plant of the Sichuan power grid was used to empirically evaluate the model. The pricing mechanism of reservoir power plants proposed in this paper considered the power grid benefits, flood control benefits, shipping benefits, and emission reduction benefits of hydropower, and allowed for the internalization of the positive externality. The hydropower grid prices based on our recommendations did not cause a dramatic impact on the local power grid; furthermore, the model helped promote the social responsibility of power companies through the pricing guidance for improving economic benefits by increasing positive externalities.

Keywords: Hydropower; Positive externality; Pricing mechanism; Social benefits; Value quantification

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1. Introduction

1.1. Study background

For quite a long time, China's hydropower has been based on the principle of cost with a reasonable return, and the pool purchase price has been determined mainly by the government, which could seriously underestimate or ignore the value of hydropower. At the same time, in comparison with other forms of energy, the hydropower pricing mechanism also has unfair pricing elements. For example, after the installation of desulfurization, denitration, and dust removal devices in coal power plants, the electricity price is adjusted higher to compensate for the cost of environmental protection investment. In addition, compensation of 0.005–0.01 yuan/kWh was granted for the transformation investment of power plants that underwent the ultra-low emission technology reform in coal power generation in 2015. Hydropower is a naturally clean energy, but the emission reduction benefits have not been reflected in the current price. Furthermore, wind power and photovoltaic systems as clean energy resources have been constantly supported by the country and each province to have higher electricity price approval (Table 1), and the renewable energy consumption quota system was granted. Hydropower is a renewable energy, but it is excluded from this system. These various difficulties have seriously affected the planning, development, production, and operation of hydropower companies. The utilization hours of hydropower have fallen sharply, and the power companies have suffered serious losses. Unable to invest in the construction of new power projects, the capital chains of some companies are on the verge of breaking, thus seriously impairing the development of hydropower in China. Taking Sichuan Province as an example, the surplus water (converted into electricity) announced in 2011–2017 was 270 million kWh, 7.6 billion kWh, 2.6 billion kWh, 9.7 billion kWh, 10.2 billion kWh, 14.1 billion kWh, and 14 billion kWh, respectively. From 2011 to 2017, the annual utilization hours of hydropower were between 3,772 and 4,097 h, with an average of 3,920 h. The installed utilization hours of these power plants were designed to average close to 4,800 h, and therefore, the average actual surplus water (converted into electricity) should be much higher than the announced values. Internationally, according to data from the US Energy Information Administration and Eurostat, in the United States, the United Kingdom, Germany, and 34 other countries, the average pool purchase price in 2017 (converted to Renminbi (RMB) according to the average exchange rate in 2017) was 0.459 yuan/kWh, and between 0.277 yuan/kWh (Sweden) and 1.485 yuan/kWh (Malta). China's pool purchase price ranked 23rd, at a low level, and there is still room for growth. It is, therefore, urgent to recognize and evaluate the value of hydropower and explore a strategy for hydropower development and management; this is also appealing to hydropower builders.

This study proposed the concept of the positive external electricity price (PEEP) and a pricing mechanism that considered, for the first time, the values of hydropower positive externality factors using the positive externality theory. The pricing mechanism of the reservoir power plant proposed in this paper

Table 1. Statistics of the average pool purchase price of power companies (2017). Unit: yuan/kWh.

Pool purchase price	Hydropower	Coal power	Gas power	Wind power	Photovoltaic power	Biomass power
Sichuan	0.25908	0.40640	0.50405	0.56593	0.81887	0.79499
The whole country	0.25893	0.37165	0.66494	0.56230	0.93990	0.76536

considered the power grid benefits, flood control benefits, shipping benefits, and emission reduction benefits of hydropower, and allowed for the internalization of the positive externality. The hydropower grid prices based on our recommendations did not have a dramatic impact on the local power grid; furthermore, the model helped promote the social responsibility of power companies through the pricing guidance for improving economic benefits by increasing positive externalities. In addition, the pricing mechanism can rationally guide the orderly planning and development of various types of power plants and promote the transition of the power market from government regulation to comprehensive marketization. However, although the main quantification method is proposed based on the positive externality factor quantification model, no specific quantitative method is proposed for the indirect tourism benefits, social construction benefits, and other negative external factors. Because the model is designed primarily for easy operation, the quantitative methods and indicators used are still imperfect. These issues will be further investigated in future studies.

1.2. Literature review

According to related studies outside China, for those countries where the power market operation mechanism is relatively well developed, the capacity market or auxiliary service market has been established, and the quality and benefits of the auxiliary service could be further improved through market competition, most have included hydropower within the scope of their renewable energy quota system. There are relatively few studies focusing on the pricing mechanisms of hydropower, whereas the research on the quantification of non-energy values of hydropower is relatively thorough. From 2010 to 2013, the American Electric Power Research Institute (EPRI) used 3 years to simulate the actual operation of the regional power market and carried out various exploratory activities in conjunction with future scenarios on power system modeling, market analysis, and cost data collection (EPRI, 2010, 2011, 2012a, 2012b, 2012c). This was the first comprehensive analysis and quantification of the non-energy benefits of conventional hydropower plants and reservoir hydroelectricity power plants.

In 2015, researchers from the Aachen University of Technology in Germany conducted a simulation study of the transmission of Norwegian hydropower to the European electricity market. The results showed that Norwegian hydropower contributed significantly to the European electricity market (Moser, 2015). Knetsch (1964) conducted a comparative analysis of the land value of several reservoirs in the Tennessee Valley of the United States, indicated that the construction of the reservoir could enhance the economic value of the surrounding land to varying degrees, and established the corresponding forecasting model by further analyzing the relationship of the indicators of land location and function to the land value. Southgate & Macke (1989) reported that hydropower development projects in developing countries had important soil and water conservation benefits and established corresponding measurement models, which were empirically verified using a hydropower development basin in Ecuador as an example. Trice & Wood (1958) measured the recreational value of the five reservoirs in the Upper Feather River Basin using the travel expense method based on the existing data of the California Water Resources Bureau combined with the U.S. Fish and Wildlife Service research results in parts of the Truckee River.

In terms of non-energy benefit quantification, domestic scholars primarily quantified the value of a single output factor. In 1987, Feng first proposed a calculation method of grid peak regulation benefits and rewards for the Sichuan power grid and proposed to reduce the thermal power load during the low valley period and increase the runoff hydropower load rate to achieve economical operation for decreasing coal combustion (Feng, 1987). In 1996, Qiu used the equivalent alternative cost and the expected increase in shipping revenue and savings in shipping costs to calculate shipping benefits (Qiu, 1996). In 2011, Luo & Wei used the energy method to define the ratio of the total energy input value of agricultural irrigation to the total energy input value of the production process as the benefit-sharing coefficient and proposed a specific method for the accurate calculation of agricultural irrigation benefits (Luo & Wei, 2011). Yang *et al.* (2004) proposed a quantitative calculation method based on the environmental sub-benefit decomposition statistics from the connotation and characteristics of the water environment and validated the method using examples.

In terms of combining various benefits with power grid prices, many domestic scholars have performed relevant studies. Li *et al.* (2004) first proposed that environmental costs should be considered in addition to the original production costs in the development of power grid prices. Cao (2009) proposed to formulate electricity prices for renewable energy based on fixed electricity prices and premium electricity prices. The premium electricity price was intended to convert the pollutant emission reduction benefits into the economic benefits of power plants. Zhang *et al.* (2009) converted the social environmental benefits, including benefits to irrigation, aquaculture, water supply, and emission reduction, generated by hydropower plants into environmental shadow costs in the production cost of hydropower plants and calculated the values using examples. Unfortunately, the quantitative methods used for specific environmental shadow costs were not shown in the report. Liu *et al.* (2015) used the ACM0002 methodology to model and calculate the carbon dioxide emission reduction price based on carbon trading, which was further used to understand the pricing mechanism of Tibetan electricity delivery. Cao *et al.* (2015) decomposed the clean energy value of hydropower into the emission reduction benefits of CO_2, SO_2, NO_x, and dust, which were used to analyze samples. Yang *et al.* (2017) proposed the green pricing method of hydropower for social and environmental benefits. For the first time in China, the social and environmental benefit rates were set as the price adjustment factors, which were reflected in the hydropower electricity grid price.

The above literature has made great progress in quantifying the value of hydropower, and many quantitative methods are worth learning. However, there is a lack of positive externality classification for hydropower values, and a comprehensive and systematic quantitative model in combination with the electricity grid pricing mechanism is missing. This study first utilized the quantitative positive externality theory to classify the hydropower values and quantify the four major positive externality factors. On this basis, a feed-in pricing model was proposed for the internalization of hydropower positive externalities, which has not been done before. This model could provide a reference for the hydropower pricing mechanism during the reform of the electric power system.

2. Methods

2.1. Identification of output elements of positive externalities

Depending on whether the externality implementer promotes or reduces the benefits of external recipients, an externality can be classified as positive or negative (Shi, 2013).

The hydropower development project is a complex system, and its output factors can be roughly divided into three categories: economic output, social output, and environmental output (Zheng *et al.*, 2016). In conjunction with the actual situation of hydropower project operation, the output factors were further refined and analyzed, and positive and negative externalities were identified according to the externality theory. The positive externality factors of hydropower projects mainly included power grid benefits and indirect tourism benefits (economic output category); disaster prevention benefits, shipping benefits, and social construction benefits (social output category); emission reduction benefits and improvement of regional water environment (environmental output category), as illustrated in Figure 1.

Within the economic output category, power grid benefits refer to the role of hydropower in regulating peak regulation and frequency, tracking load rapid rise and fall, and acting as load backup and accident backup (Gao, 2012), thereby reducing the coal consumption and life wear-off of thermal power plants during the start–stop and regulation processes. The indirect tourism benefits refer to the large number of tourists attracted by hydropower projects, which has driven the development of related industries, including food catering and accommodation, and indirectly promoted the economic development of the region.

With regard to the social output category, the disaster prevention benefits mainly include flood control and ice prevention benefits. According to the Economic Evaluation Standards for Water Conservancy Construction Projects, the flood damage that can be reduced or exempted from water conservancy construction projects and the increased land development and utilization values are considered as flood control benefits. Ice prevention benefits mainly refer to the hydropower project of the northern rivers of China relying on the hydropower plants' good regulation ability to exempt or mitigate ice flood disasters. Shipping benefits refer to improving the original navigation conditions, broadening the navigation channels, and increasing the benefits of transportation (including both passenger and freight transportation).

In the environmental output category, emission reduction benefits refer to the role of hydropower in reducing pollutants and greenhouse gas emissions when replacing other energy sources. The

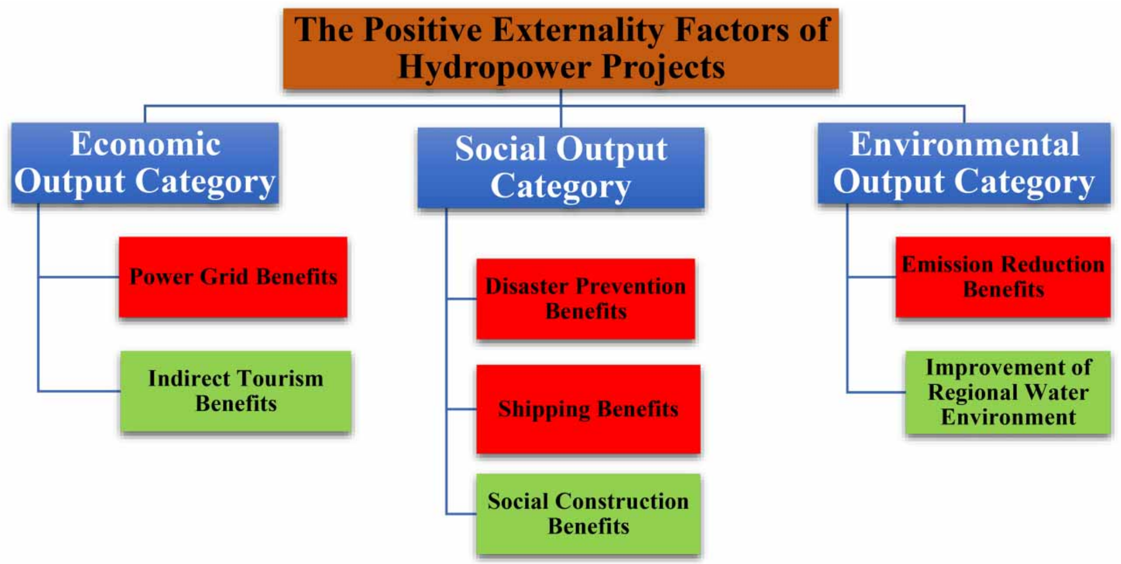

Fig. 1. The composition of the positive externality factors of hydropower projects.

improvement of water environment mainly refers to the construction of a hydropower project reservoir area to reduce the turbidity of a body of water to a certain extent, reduce the hardness of water, and reduce the possibility of increased toxicity caused by an over-alkaline environment in the regional water environment.

Despite these significant public resource attributes, hydropower development entities do not benefit from them in the current economic environment. At the same time, hydropower projects also have some negative external factors that cause damage and adverse effects on the economy, society, and the environment, such as submerged losses, resident resettlement, and damage to the river and surrounding ecological environment.

The purpose of this paper is to build a non-energy benefit internality model that can be widely used and monetize positive external factors. This paper considers the actual operation of hydropower and selects four main subitems that contribute the most to society and can be quantified using the current data, namely power grid benefits, flood control benefits, shipping benefits, and emission reduction benefits.

In addition to the above four positive external factors, there are other positive external factors, but they can often obtain the corresponding benefits through market-oriented operations such as irrigation and recreation. Most of the negative external factors of hydropower plants have been included or converted into the construction cost and other positive external factors of hydropower plants. For example, submerged losses, resettlement costs, and cultural relics protection costs brought about by hydropower plant construction are included in the total investment cost of hydropower plants. In the research of this paper, these three factors have been converted into the investment of hydropower that is allocated to the year. The flood disaster loss has also been deducted in the calculation of flood control benefits. Furthermore, there are still disputes about the ecological impact of hydropower plants on the surrounding environment. For example, after the completion of some hydropower plants, the water quality improves due to the reduced amount of sediment discharged downstream, but at the same time, this improvement in water quality leads to the intensification of downstream scouring and the reduction of fish species. These negative externalities of different power stations often vary greatly due to different natural conditions and are difficult to calculate qualitatively. Considering that other positive external factors and negative external factors can be offset to some extent, this paper uses power grid benefits, flood control benefits, shipping benefits, and emission reduction benefits as positive external factors, which can clearly reflect the hydropower plants' comprehensive benefits. Other issues including positive external factors and negative external factors remain to be further investigated in future studies.

2.2. Quantification method of positive externality factors

2.2.1. Power grid benefits. Based on the literature and the equivalent alternative methods, this paper classified the benefits of hydropower grids into two categories: reducing grid operation costs and improving the reliability of the grid. In this paper, the hydropower plant to be studied is referred to as the basic plan, and the coal power plant to be used for comparison is referred to as the alternative plan. Based on the actual operating data of the power grid, this study calculated the power system costs of the basic plan and the alternative plan separately. In addition, through the power outage loss method and the consideration of the reliability benefit of the power system (Xu, 1997; Xu *et al.*, 2001; Xu *et al.*, 2006), the difference of the total benefits of the above two plans was expressed as the annual cost savings of hydropower plants (power grid benefits).

The detailed calculation steps for the power grid benefits of the hydropower plant are as follows:

The first step is to establish a power system annual cost model to calculate the annual cost of the basic plan and the alternative plan. The annual cost is expressed by *Cost*. The annual cost difference between the two plans is the power grid benefit of the hydropower plant in question. The annual cost calculation of the system is expressed by the following equation:

$$Cost = \left(\sum_{k=1}^{n} H_k/T_k + \sum_{r=1}^{m} H_r/T_r\right) + \left(\sum_{k=1}^{n} H_k S_k + \sum_{r=1}^{m} H_r S_r\right) + \sum_{r=1}^{m} P_r Q_r E_r + \sum_{r=1}^{m} W_r M_r N_r + \mathrm{EENS} \cdot A \tag{1}$$

The annual cost of the power system is composed of five parts. The first part is the investment of thermal power and hydropower on a yearly basis in the basic plan or the alternative plan, that is, the depreciation sharing. Given that the difference between the two plans is required here, only the cost of the hydropower plant to be studied and the alternative thermal power is considered. Parameters in (2) are described in Table 2.

The second part is the annual operating cost of all power plants in the power system (excluding coal consumption and thermal power start–stop costs). The third part is the annual coal consumption cost of all thermal power plants in the power system. The fourth part is the annual start–stop loss of all thermal power plants in the power system. And the fifth part is the unreliable damage cost of the power system.

Table 2. Parameters in the annual cost calculation of the system.

Symbol	Description
n	The number of all types of hydropower of the power system
m	The number of all types of thermal power of the power system
H_k	The total investment cost of the kth hydropower plant
H_r	The total investment cost of the rth thermal power plant
T_k	The calculation period of the kth hydropower plant, which generally refers to the design life of the hydropower plant or the calculation period before a major renovation is required
T_r	The calculation period of the rth thermal power plant, which generally refers to the design life of the thermal power plant or the calculation period before a major renovation is required
S_k	The ratio of the annual operating cost of the kth hydropower plant to the total investment cost of the hydropower plant
S_r	The ratio of the annual operating cost of the rth thermal power plant to the total investment cost of the thermal power plant
P_r	The unit average coal price of the rth thermal power plant, including the freight of the coal arriving at the power plant and the cost of coal storage at the thermal power plant converted to unit coal price
Q_r	The unit coal consumption rate of the rth thermal power plant
E_r	The annual power generation of the rth thermal power plant
W_r	The installed capacity of the rth thermal power plant
M_r	The start–stop loss of the rth thermal power plant equivalent to the unit installed capacity
N_r	The average annual start and stop times of the rth thermal power plant
EENS	The annual expected energy not supplied by the power system
A	The annual power shortage loss charge of the power system equivalent to the unit power

The next step is to calculate the difference between the electricity grid benefits of the two plans to obtain the power grid benefits of the hydropower plant in question by using the following equation:

$$B_1 = Cost_m - Cost_n \tag{2}$$

where B_1 represents the power grid benefits, $Cost_m$ represents the annual cost of the alternative thermal power system, and $Cost_n$ represents the annual cost of the basic plan of the hydropower system.

2.2.2. Flood control benefits. Presently, scholars have reported intensive studies on the calculation methods of flood control benefits. In general, the main methods are as follows: the loss reduction methods (including the frequency method and the annual series method), the insurance premium method, the optimal equivalent substitution measure method, and the stable production growth method. This paper mainly focused on the flood damage frequency method to calculate the flood control benefits of the hydropower plant (Bai, 1995; Fang & Dai, 1995; Shi, 1995).

The flood frequency method is to calculate the loss value caused by floods of different frequencies both when there is and when there is not a flood control project and then identify the average loss value for each of these two cases in this area. The difference between the two is the benefit of the construction of this flood control. Specifically, the calculation is divided into two steps.

Step one: Separately calculate the loss value caused by floods with different frequencies when there is a flood control project and when there is no flood control project. By investigating and collecting the availability of flood control projects, the economic output value and the flood damage value of each inundated area can be calculated. The loss value caused by floods of different frequencies is calculated as follows:

$$E_P = \sum_{i=1}^{n} E_{P,i}(1+\alpha) \tag{3}$$

where E_P denotes the flood damage with frequency P; $E_{P,i}$ denotes the flood loss of the ith region with frequency P; n is the nth flooded area; and α is the indirect loss coefficient which is generally 10–15% (in this study, α is 10%).

Step two: Calculate the average annual flood damages.

Based on the project grade and the importance of the flood control object, a certain frequency step is selected to calculate the average annual flood damages. For a hydropower plant with a designed flood frequency of 1/100 or 1/50, the frequency of floods used in economic calculations is often 1%, 2%, 3.33%, 5%, 10%, and 33.33% in China because floods at these frequencies can well represent all possible flood situations:

$$B_2 = \frac{\sum_{P=0}^{1} \Delta P \overline{E_{P_{i,i+1}}}}{\sum_{P=0}^{1} \Delta P} \tag{4}$$

where B_2 indicates the multi-year average flood loss when there is no flood control project (the selected frequencies are the ones that the flood control project can resist), that is, the flood prevention benefit; ΔP

is the difference between the adjacent two frequencies, that is, the selected frequency step; and $\overline{E_{P_{i,i+1}}}$ represents the average of the flood losses of two adjacent frequencies.

2.2.3. Shipping benefits. When a hydropower plant is built on a river section with shipping requirements, the upper reaches of the central hub have an elevated water level, which could inundate the shoal to form an excellent deep water channel in the reservoir area. In the lower reaches of the central hub, due to the regulation effect of the reservoir, the flow increases during the dry season, and the depth of the voyage increases; the flood peaks are flattened during the flood period with the reduced flow rate. The duration of the normal flow period, which is favorable for shipping, increases, thereby further reducing shipping costs, increasing navigation capacity, and enhancing the competitiveness of shipping transport. Considering the entire shipping system and transportation process, the shipping benefits can be calculated indirectly by the equivalent alternative power method (Tang *et al.*, 1991; Guo, 2010).

Assume that the river channel where a hydropower plant project is located has a shipping function. Since the freight transportation volume of the river channel is increased to W t due to the construction of the hydropower plant reservoir, the W t freight and its volume will not be transported via shipping but by other routes, including railway, highway, or a combination of railway and highway. Then, the optimal equivalent alternative plan is to transport these freight volumes to the destination with the least cost. The net benefit of shipping is obtained by subtracting the conversion cost of the shipping channel from the conversion cost of the optimal equivalent alternative, which can be expressed by the following equation:

$$B_3 = C_0 - C_\mathrm{s} \tag{5}$$

where B_3 is the annual cost saved by shipping, that is, the annual benefit of shipping; C_0 represents the cost of transporting the annual freight volume W with the optimal equivalent alternative; and C_s denotes the cost of shipping the annual volume W through the river.

2.2.4. Emission reduction benefits. The hydropower project is an integral part of the international clean development mechanism (CDM) market (Zhang & Li, 2008). As early as the 2002 World Summit on Sustainable Development in South Africa, the role of hydropower, including large-scale hydropower, as a clean and renewable energy source had been fully recognized by the international community (Huo, 2006). This paper mainly analyzed the emission reduction benefits of hydropower development for CO_2, SO_2, NO_x, and dust.

In the calculation equation, the emission reduction benefits of CO_2, SO_2, NO_x, and dust can be obtained by the ACM0002 methodology and environmental degradation cost kernel algorithm (UNFCCC, 2006; UNFCCC, 2009; Yu *et al.*, 2012).

The CO_2 emission reduction benefit calculation model is:

$$\begin{cases} \mathrm{AB}_{\mathrm{CO_2},y} = p_y \times \mathrm{ER}_y \\ \mathrm{ER}_y = \mathrm{BE}_y - \mathrm{PE}_y - L_y \\ \mathrm{BE}_y = \mathrm{EG}_y \times \mathrm{CM} \\ \mathrm{CM} = w_{\mathrm{OM}} \times \mathrm{OM} + w_{\mathrm{BM}} \times \mathrm{BM} \end{cases} \tag{6}$$

where $\mathrm{AB}_{\mathrm{CO_2},y}$ is the carbon dioxide emission reduction benefit generated by the hydropower project in year y; p_y is the annual average transaction price of carbon emissions; ER_y is the annual CO_2 emission reduction of hydropower projects; BE_y is the CO_2 baseline emissions specified by ACM0002 methodology; PE_y is the total CO_2 emission from hydropower operation in year y; L_y is the total CO_2 leakage from hydropower operation; EG_y is the hydropower project grid power in year y; CM is the emission factor of the grid where the hydropower project is located; OM is the marginal emission factor of electricity; BM is the marginal emission factor of capacity; and w_{OM} and w_{BM} are the respective weight coefficients of OM and BM.

The SO_2 emission reduction benefit calculation model is:

$$\begin{cases} \mathrm{AB}_{\mathrm{SO_2},y} = \mathrm{UEC}_{\mathrm{SO_2,y}} \times R_{\mathrm{SO_2},y} \\ \mathrm{UEC}_{\mathrm{SO_2,y}} = \mathrm{EC}_{\mathrm{SO_2},y}/V_{\mathrm{SO_2},y} \\ \mathrm{EC}_{\mathrm{SO_2},y} = \mathrm{EC}_y \times A_{p,\mathrm{SO_2}}/(A_{p,\mathrm{NO}_x} + A_{p,\mathrm{SO_2}} + A_{p,\mathrm{du}}) \end{cases} \tag{7}$$

where $\mathrm{AB}_{\mathrm{SO_2},y}$ is the SO_2 emission reduction benefit generated by hydropower projects for year y; $R_{\mathrm{SO_2},y}$ is the SO_2 emissions reduced by hydropower in year y; $\mathrm{UEC}_{\mathrm{SO_2,y}}$ is the unit degradation cost caused by SO_2 pollution in year y; $V_{\mathrm{SO_2},y}$ is the SO_2 emissions in year y; $\mathrm{EC}_{\mathrm{SO_2},y}$ is the environmental degradation cost of SO_2 pollution in year y; EC_y is the atmospheric environmental degradation cost in year y; $A_{p,\mathrm{SO_2}}$ is the pollutant equivalent value of SO_2; A_{p,NO_x} is the pollutant equivalent value of NO_x; and $A_{p,\mathrm{du}}$ is the pollutant equivalent value of dust.

The NO_x emission reduction benefit calculation model is:

$$\begin{cases} \mathrm{AB}_{\mathrm{NO}_x,y} = \mathrm{UEC}_{\mathrm{NO}_x\mathrm{,y}} \times R_{\mathrm{NO}_x,y} \\ \mathrm{UEC}_{\mathrm{NO}_x\mathrm{,y}} = \mathrm{EC}_{\mathrm{NO}_x,y}/V_{\mathrm{NO}_x,y} \\ \mathrm{EC}_{\mathrm{NO}_x,y} = \mathrm{EC}_y \times A_{p,\mathrm{NO}_x}/(A_{p,\mathrm{NO}_x} + A_{p,\mathrm{SO_2}} + A_{p,\mathrm{du}}) \end{cases} \tag{8}$$

where the symbol definitions are similar to those of the SO_2 emission reduction benefit model.

Dust emission reduction benefits are:

$$\begin{cases} \mathrm{AB}_{\mathrm{du},y} = \mathrm{UEC}_{\mathrm{du},y} \times R_{\mathrm{du},y} \\ \mathrm{UEC}_{\mathrm{du,y}} = \mathrm{EC}_{\mathrm{du},y}/V_{\mathrm{du},y} \\ \mathrm{EC}_{\mathrm{du},y} = \mathrm{EC}_y \times A_{p,\mathrm{du}}/(A_{p,\mathrm{NO}_x} + A_{p,\mathrm{SO_2}} + A_{p,\mathrm{du}}) \end{cases} \tag{9}$$

where the symbol definitions are similar to those of the SO_2 emission reduction benefit model. The calculated sum of the above stated CO_2, SO_2, NO_x, and dust emission reduction benefits could yield the hydropower emission reduction benefit B_4.

$$B_4 = \mathrm{AB}_{\mathrm{CO_2}} + \mathrm{AB}_{\mathrm{SO_2}} + \mathrm{AB}_{\mathrm{NO}_x} + \mathrm{AB}_{\mathrm{du}} \tag{10}$$

2.3. Positive externalities of electricity price model

The theory of the two-unit electricity price is to split the electricity price into two parts: the basic electricity price and the electricity degree electricity price. The basic electricity price has no connections with the power generation but is used to compensate the fixed cost of the power plant. The electricity degree electricity price is related to the amount of electricity generated by the variable cost. With the two-unit price system, it is easier to achieve reasonable compensation costs and reasonably determines the principle of returns. Currently, China's electricity market is mainly engaged in the implementation of a single electricity price. However, according to the theory of two-unit electricity price, compensation in the form of additional electricity prices can be provided for some types of energy production investments that are not included in the basic electricity price, such as the desulfurization and denitration of coal power (Ma & Wang, 2003; Chen, 2008; Zhang *et al.*, 2016). Therefore, with reference to the practice of thermal power plants having an additional electricity price for environmental protection, this study proposes the concept of PEEP, which is the additional external electricity price that quantifies the positive external benefits of the hydropower station (or another type of power plant with positive external benefits). On this basis, a power price model including basic electricity price and PEEP was established, that is, the PEEP model. By formulating additional items to allow the electricity price to reasonably reflect the positive externality of hydropower plants, it provides a reference for the government's next electricity price reform.

According to the above calculation method, the benefit value of each major positive externality factor of the hydropower plant is obtained. Considering the above-mentioned positive externality factor benefits, if the integrated electricity price of hydropower is P (composed of basic electricity price and PEEP), the basic electricity price of hydropower is P_0, and the PEEP is P', then

$$P = P_0 + P' = P_0 + \sum_{i=1}^{n} \theta_i B_i / Q \tag{11}$$

where P_0 is the cost price calculated from the cost of power generation or by directly taking the pool purchase price. B_i represents the ith positive externality; this study mainly considers four major positive externalities: power grid benefits, flood control benefits, shipping benefits, and environmental benefits. The variable n is the number of items with positive external benefits, and here, we take $n = 4$. θ_i is the ith balance coefficient, which is used to balance the calculation deviation that may be caused by the method itself and to reflect the management's consideration of the ith positive externalities. Here, we take the value of θ_i ($i = 1, 2, 3, 4$) equal to θ, and then the formula for calculating the integrated electricity price becomes (12). Q is the annual power generation of hydropower plants. In the actual operation process, the positive externality of the power plant and the annual power generation amount of the previous year are used as the basis for calculating the integrated electricity price of the current year.

$$P = P_0 + P' = P_0 + \sum_{i=1}^{4} \theta B_i / Q \tag{12}$$

3. Case analysis

This study used hydropower plant S of the Sichuan power grid as an example for analysis. Hydropower plant S is an integrated hydropower plant with various benefits, including flood control, navigation shipping, irrigation, water supply, and power generation. The installed capacity of hydropower plant S is 1.10 million kW with a total investment of 17.223 billion yuan. It has an annual adjustment capacity and is a control project in the gradual development plan of the Yangtze River mainstream. The control area of the dam site accounts for 35% of the area of the basin. In 2014, all units of hydropower plant S were executed into operation. Based on the plant's 2017 operational data, this study calculated the positive externalities of the power plant in 2017 using the above-described method, which could serve as the basis for considering the PEEP and the integrated electricity price of hydropower plant S in 2018.

3.1. Power grid benefits

The designed operation life cycle of hydropower plant S is 40 years, and the annual operating cost is calculated based on 1.5% of the total investment. The alternative uses high-benefit coal plants that meet the power requirements of the hydropower system to the same extent. The total investment of the alternative thermal power plant is 4.95 billion yuan, and the unit cost is 4,500 yuan/kW. The design life cycle of the alternative thermal power plant is 40 years, and the coal consumption rate is 309 g/kWh based on the national standard power consumption of 6,000 kW and above. The annual utilization hours of hydropower plant S is 2,938–2,736 h. Based on 2,938 h for calculation, the annual power generation is 3.2318 billion kWh. The coal price based on the average value of coal in 2017 was 627.4533 yuan/t, and the ratio of the annual operating cost of the alternative thermal power plant was calculated at 3.5% of its investment.

According to the calculation results of the start–stop loss in the literature (Yan & Chen, 2015), the calculated loss of a 1,100 MW unit start–stop was 1.3469 million yuan each time. If the number of start–stops per year was taken as six times based on the actual running value of large-scale thermal power plants in Sichuan, the annual start–stop loss was 808.148 million yuan. As the probability of the annual power shortage in Sichuan Province is almost negligible, the EENS values of the proposed two power systems are both zero.

According to Equation (2), the power grid benefit B_1 for hydropower was 242.7528 million yuan.

3.2. Flood control benefits

According to the flood control effect of hydropower plant S, the loss values of flood in different middle and lower reaches of the Yangtze River were used as the flood control benefits of hydropower plant S. According to the actual annual flood damage, the corresponding flood frequencies, and the economic development level of the counties and cities in the middle and lower reaches of the Yangtze River, the flood damage losses (except for indirect loss) at different flood frequencies were calculated according to Equation (3), as shown in Table 3.

Because both cities G and H have the mainstream of the Yangtze River and the tributaries, hydropower plant S was only effective in the flood control of the mainstreams of the G and H cities, whereas the flood control benefits in the tributaries were marginal. The average annual flood control benefits for cities G and H were calculated based on 50% of the flood control benefits in the table.

The calculation of the annual average flood damages was based on the method shown in Equation (4). The average annual flood control benefit of hydropower plant S to the middle and lower reaches of the Yangtze River was 200.0217 million yuan (calculated based on price in the year 2012), and the price converted into the year 2017 was 219.9665 million yuan.

Table 3. Loss values of flood at various frequencies in different regions. Unit: 10,000 yuan.

Frequency (%)	A	B	C	D	E	F	G	H
1	36,671.6	40,173.0	43,294.2	23,756.8	59,666.9	17,260.5	59,136.7	34,643.3
2	19,778.1	33,315.9	33,475.8	26,088.2	45,753.9	18,186.6	48,807.6	28,623.8
3.33	17,111.3	37,414.0	31,478.8	18,324.9	45,975.1	18,909.8	39,487.8	23,563.3
5	23,096.7	24,254.1	23,130.6	15,526.0	0	11,507.4	33,775.3	15,455.1
10	12,548.7	9,366.2	8,761.3	9,661.7	0	9,959.8	20,356.4	8,167.3
33.3	195.6	317.8	344.1	391.2	0	202.7	466.7	0.0
50	0	0	0	0	0	0	0	0

Notes: The loss values in this table are calculated based on the 2012 price.

3.3. Shipping benefits

After the completion of hydropower plant S, the mainstream channel of the canalization was about 165 km, increasing the downstream dry season flow rate by 108 m^3/s, and the annual designed navigation capacity of the hub was 3.181 million tons (Mt)/year. Shipping benefits were determined based on the principle of comparing the situations of 'with project' and 'without project'. In regard to the actual traffic situation in the reservoir S area, there is a second-grade road and a third-grade road connecting the upstream and downstream of the channel, with annual traffic capacities of 5.02 and 2.30 Mt, respectively. When there was no project S, the traffic volume was shared by the existing water transport and road transport. The original navigation capacity of the river section was 325,400 t. When there was project S, the increase in transportation volume was entirely attributed to water transport. The freight transportation rate for water transportation was 0.0801 yuan/(t km), and the road freight rate was 0.595 yuan/(t km). In 2017, the dam capacity of hydropower plant S was 1.904 Mt, and the increased traffic was 1.5786 Mt. The shipping benefits of hydropower plant S in 2017 were calculated to be 134.1155 million yuan by Equation (5).

3.4. Emission reduction benefits

The submerged area of hydropower plant S at the highest water level is 85.6 km^2, and the power density ω of hydropower plant S (the ratio of the installed capacity to the submerged area at the highest water level of the reservoir) was calculated to be 12.85 W/m^2. The installed capacity and power density met the ACM0002 methodology conditions, so the ACM0002 method was used to calculate the carbon dioxide emission reduction benefit of hydropower plant S. The average annual trading price of China's carbon emissions trade was used as the average annual transaction price of carbon emissions. The average price was 15.66425 yuan/t. The carbon dioxide emission reduction benefit of hydropower plant S in 2017 was calculated from Equation (6):

$$\mathrm{AB}_{\mathrm{CO_2},y} = p_y \times \mathrm{ER}_y = 27.4457\,(\text{million yuan}).$$

The environmental degradation cost kernel algorithm model established by (7), (8), and (9) can be used to calculate SO_2, NO_x, and dust emission reduction benefits. Given that the environmental degradation cost data was not available after 2008, it was difficult to apply here to calculate environmental emission reduction benefits based on the emissions of SO_2, NO_x, and dust. According to the actual operation data of coal power plants in Sichuan Province, the total emission level of SO_2, NO_x, and dust per unit of thermal power (converted into yuan) generally accounts for 10–15% of the unit's CO_2 emission level (converted into yuan). Here, the total emission reduction benefit of SO_2, NO_x, and dust was estimated as 12% of the CO_2 emission reduction benefit, so the 2017 annual emission reduction benefit of hydropower plant S is $B_4 = \mathrm{AB}_{\mathrm{CO}_2} + \mathrm{AB}_{\mathrm{SO}_2} + \mathrm{AB}_{\mathrm{NO}_x} + \mathrm{AB}_{\mathrm{du}} = \mathrm{AB}_{\mathrm{CO}_2} + \mathrm{AB}_{\mathrm{CO}_2}{*}12\% = 30.7391\,(\text{million yuan})$.

4. Discussion

By combining hydropower plant S' power grid benefits, flood control benefits, shipping benefits, and emission reduction benefits, the positive externalities of hydropower plant S in 2017 were equivalent to 627.574 million yuan, and the integrated electricity price can be calculated by (12). The percentage of each positive externality element is shown in Figure 2. It can be seen that the power grid benefit (accounting for 39%) and flood control benefit (accounting for 31%) account for the largest proportions; the two benefits add up to 70% of the total. The shipping benefit is relatively small (accounting for 21%), and the emission reduction benefit is the smallest (accounting for only 5% of the total).

According to the needs of the discussion, the basic electricity price P_0 was set as 0.25908 yuan/kWh (the average pool purchase price of hydropower in Sichuan Province in 2017) and 0.21317 yuan (the annual cost of electricity generated by hydropower plant S divided by the annual power generation of hydropower plant S). By varying the value of θ, the integrated electricity price can take different values, as shown in Table 4. The table shows that when the θ-value increases from 0 to 1, the integrated electricity price increases from 0.25908 to 0.45327 yuan/kWh, and the weights of the comprehensive

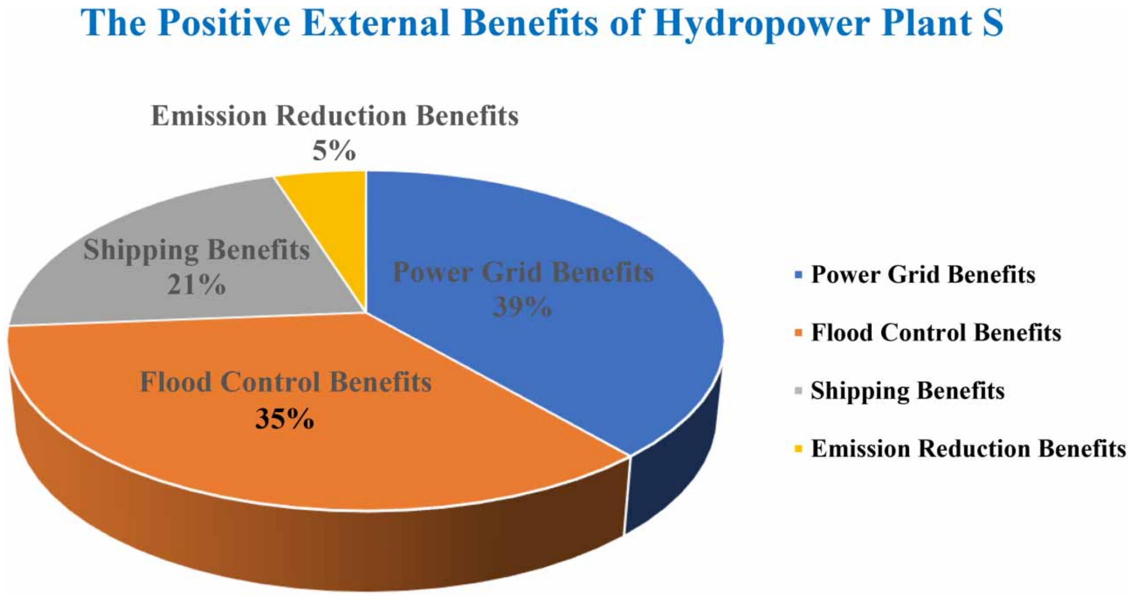

Fig. 2. The proportion of positive external benefits of hydropower plant S.

Table 4. Statistics of integrated electricity prices under different parameters. Unit: yuan/kWh.

Integrated electricity price		θ-value									
		1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
P_0	0.25908	0.45327	0.43385	0.41443	0.39501	0.37559	0.35617	0.33675	0.31734	0.29792	0.27850
	0.21317	0.40736	0.38794	0.36852	0.34910	0.32968	0.31026	0.29084	0.27143	0.25201	0.23259

benefits, including power grid benefits, flood control benefits, shipping benefits, and emission reduction benefits, also increase.

I. Using the cost price of hydropower plant S as the basic electricity price P_0.

1. Take Sichuan Province as an example, the integrated electricity price obtained by taking any value (0–1) of θ is lower than the average pool purchase price of gas power generation, wind power generation, photovoltaic power generation, and biomass power generation. When the value of θ is less than 1, the integrated electricity price is less than the average pool purchase price of coal power generation. The comparison of these electricity prices is shown in Figure 3.
2. Take the whole country as an example, the integrated electricity price obtained by taking any value (0–1) of θ is lower than the average pool purchase price of gas power generation, wind power generation, photovoltaic power generation, and biomass power generation. When the value of θ is equal to 1, the calculated integrated electricity price is higher than the national average pool purchase price by 9.6%.

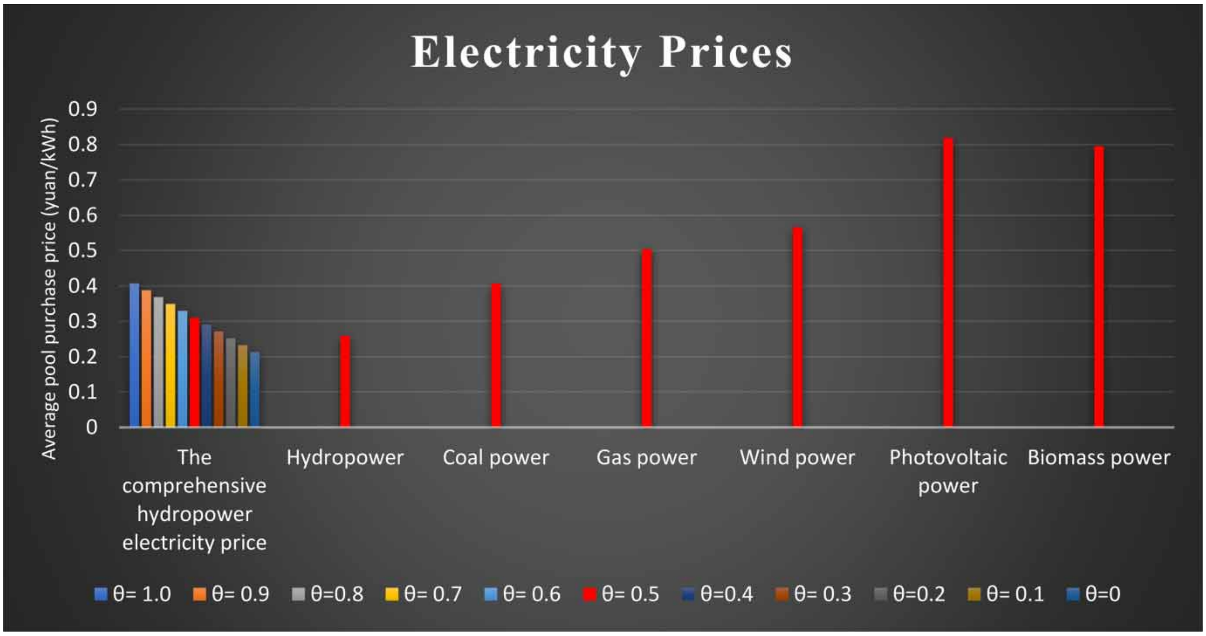

Fig. 3. Comparison of average pool purchase prices of different power companies and integrated electricity prices under different parameters. The cost price of hydropower plant S in 2017 was used as the basic electricity price P_0. Unit: yuan/kWh.

II. Using the average pool purchase price of hydropower generation in Sichuan Province in 2017 as the basic electricity price P_0.

1. Take Sichuan Province as an example, the integrated electricity price obtained by taking any value (0–1) of θ is lower than the average pool purchase price of gas power generation, wind power generation, photovoltaic power generation, and biomass power generation. When the value of θ is equal to 1, the calculated integrated electricity price is higher than the average pool purchase price of 11.5% of coal power generation in Sichuan Province. The comparison of these electricity prices is shown in Figure 4.
2. Take the whole country as an example, the integrated electricity price obtained by taking any value (0–1) of θ is lower than the average pool purchase price of gas power generation, wind power generation, photovoltaic power generation, and biomass power generation. When the value of θ is equal to 1, the calculated integrated electricity price is higher than the national average pool purchase price of 22.0% of coal power generation.

Currently, the pricing mechanism of China's hydropower does not allow the positive externalities of hydropower (including hydropower peak regulation, frequency modulation, flood control, shipping benefits, and the emission reduction of pollutants, such as carbon dioxide and sulfur dioxide) to be well reflected in the price of hydropower. Hydropower plants compete in the market with thermal power plants and can only rely on power generation revenue to maintain operations. Table 1 shows the average pool purchase price of power companies in Sichuan Province and the whole country in

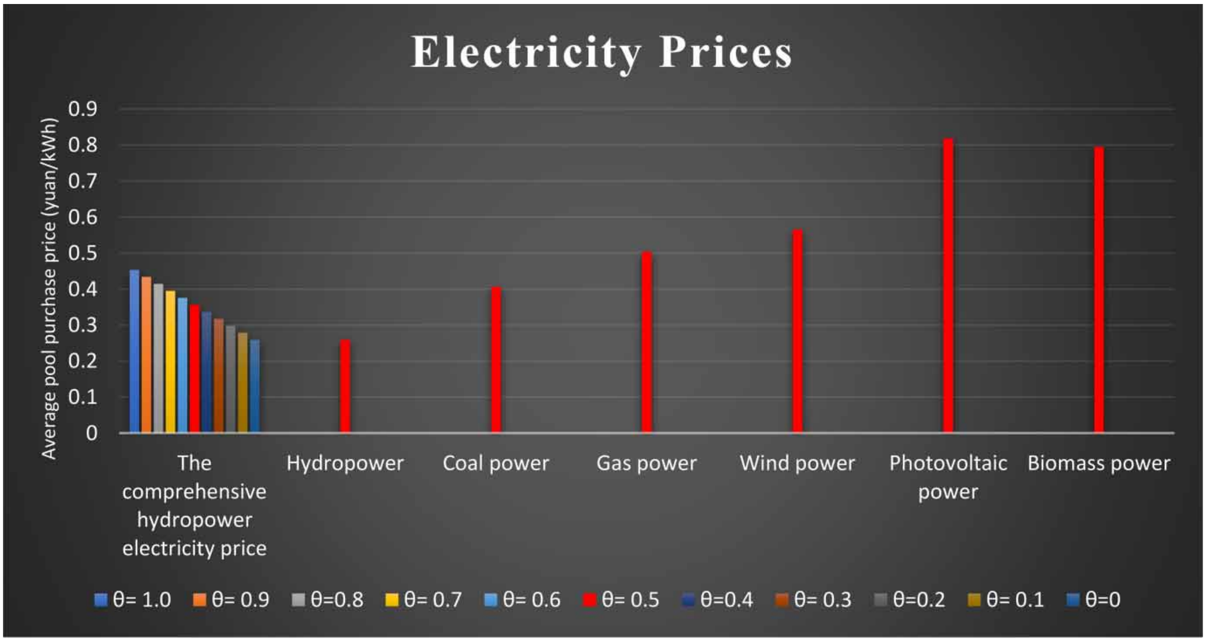

Fig. 4. Comparison of average pool purchase prices of different power companies and integrated electricity prices under different parameters. The average pool purchase price of hydropower generation in Sichuan Province in 2017 was used as the basic electricity price P_0. Unit: yuan/kWh.

2017, including hydropower, coal power, gas power, wind power, photovoltaic power, and biomass power. The data showed that the average pool purchase price of hydropower generation was the lowest in Sichuan Province and the whole country, followed by coal power generation. Therefore, considering the PEEP is not only necessary but also feasible in the current pricing environment. With the over-production of power generation, the competition among hydropower plants in Sichuan Province has intensified, resulting in a significant reduction in revenue from power generation in hydropower plants. This situation directly affects the normal operation of the plant, which, in turn, affects the development of other related positive externality benefits. This is not conducive to the sustainable development of hydropower and the electricity market as well as the fairness of competition. The pricing mechanism proposed in this study considering positive externalities will be largely conducive to the sustainable development of hydropower and the fairness of competition in the electricity market.

Based on the above results, it is quite obvious that by reasonably selecting the values of P_0 and θ in the quantitative calculation described in this paper, the effects of the power grid benefits, flood control benefits, shipping benefits, and emission reduction benefits of hydropower plant S can be reasonably quantified and reflected in the electricity price.

First, the value of the parameter θ must be selected. The current pool purchase prices of all power companies are reasonably increased on the basis of basic costs, and little consideration has been given to the benefits of public welfare. Therefore, directly quantifying the benefits to the power grid, flood control, shipping, and emission reduction according to the ratio of 1:1 (θ is set to 1.0) is not only inconducive to the realization of these benefits but also difficult to implement in actual policies. Meanwhile, power grid benefits, flood control benefits, shipping benefits, and emission reduction benefits have the nature of two-way benefits, namely the hydropower plant is generating these additional positive external benefits and also enjoying the results of such benefits. For example, when a power plant brings flood control benefits and shipping benefits downstream, this plant also receives the flood control benefits and shipping benefits brought by the upstream power plants. The emission reduction benefit is a reciprocal community of interests within a larger scope. Therefore, the value of θ is recommended to be appropriately increased or decreased based on the actual capacity of the power plant, the pool purchase price of other power plants, and the economic development level of the local area on the basis of 0.5.

Second, the value of the basic electricity price P_0 should be chosen. When P_0 is determined by the cost price, even though θ is taken as 1, the integrated electricity price of the hydropower can fully quantitatively reflect the positive external benefits while maintaining the price competitiveness comparable to that of the coal power plant (Sichuan). When the value of θ is smaller, this price advantage is more pronounced. When P_0 is selected as the calculated cost price of 0.21317 yuan/kWh (and θ is 0.5), the calculated integrated electricity price is 0.31026, and the electricity price return can be increased by 19.8%, which has a mild impact on the current market pricing system. Therefore, it is better for the pricing guide to select the cost price as P_0 and to obtain profits through the quantification of positive external benefits.

Lastly, this study used the typical hydropower plant S in Sichuan as an example to analyze the pricing mechanism. The pricing mechanism can be extended to other types of power plants in Sichuan Province by considering other types of power plants and conducting a systematic analysis of power generation costs and the positive external benefits of coal, gas, wind, photovoltaic, and biomass power plants. The integrated electricity price level of each power plant after considering positive external benefits should be compared and analyzed to provide a more comprehensive picture when adjusting the pricing mechanism for the government and electricity providers.

5. Conclusion

Almost all reservoir power plants in China take responsibility for water resources regulation to varying degrees and have certain public welfare functions. This study proposed a grid pricing mechanism for reservoir power plants based on market electricity prices as well as the positive externality electricity price, which has never before been considered in the grid price. The positive externality electricity price was calculated by quantifying the values of positive externality factors. Taking a typical hydropower plant in Sichuan Province as an example, the model was empirically analyzed, and the conclusions obtained are as follows:

1. In the integrated electricity price of hydropower generation, the consideration of the comprehensive benefits of hydropower stations can more fully reflect the value of hydropower stations, help solve the current development difficulties of hydropower enterprises, and promote the long-term healthy and sustainable development of hydropower. Furthermore, the pricing mechanism is also conducive to the adjustment and improvement of the energy structure and the realization of national emission reduction targets. The integrated electricity price obtained based on our recommendations has not caused a dramatic impact on the local power grid.
2. The pricing mechanism of the reservoir power plants based on the quantification of the value of positive externality factors considers the power grid benefits, flood control benefits, shipping benefits, and environmental benefits of hydropower, and allows for the internalization of the above factors. In addition, the quantitative model features adjustable model parameters based on the characteristics of power systems in different regions, which enhances the adaptability of the model itself.
3. The value of the parameter θ is preferably around 0.5. Through discussion, we believe that the value of θ is taken as an appropriate increase or decrease based on the on-grid price of itself and other power stations (including coal, photovoltaic, and wind power) and the economic development level of the local area. Thus, it can well balance the relationship between the traditional mechanism of grid pricing and the actual contradiction, and it can also reflect the positive externalities more reasonably from a global perspective.
4. The selection of the basic electricity price P_0 is reasonable at the cost price. Compared with the pool purchase price, the integrated electricity price is calculated by selecting the cost price, which not only has better price competitiveness but also can reduce the impact on the current electricity price, making the external electricity price more realistic and operable.

This pricing guide also promotes the social responsibility of power companies by providing increases in economic benefits to the company in exchange for the company increasing their contributions to social benefits.

The shortcomings of this model and the recommendations for further studies are as follows:

1. Although the main quantification method is proposed based on the positive externality factor quantification model, no specific quantitative method is proposed for the indirect tourism benefits or social construction benefits.
2. Since the model is designed primarily for easy operation, the quantitative methods and indicators used are still imperfect. For example, the calculation of the cost of environmental degradation of

air pollution lacks data and model support. This problem is one of the main study directions for further research.

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