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A Three-Part Electricity Price Mechanism for Photovoltaic-Battery Energy Storage Power Plants Considering the Power Quality and Ancillary Service

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Abstract: To solve the problem of solar abandoning, which is accompanied by the rapid development of photovoltaic (PV) power generation, a demonstration of a photovoltaic-battery energy storage system (PV-BESS) power plant has been constructed in Qinghai province in China. However, it is difficult for the PV-BESS power plant to survive and develop with the current electricity price mechanism and subsidy policy. In this paper, a three-part electricity price mechanism is proposed based on a deep analysis of the construction and operation costs and economic income. The on-grid electricity price is divided into three parts: the capacity price, graded electricity price, and ancillary service price. First, to ensure that the investment of the PV-BESS power plant would achieve the industry benchmark income, the capacity price and benchmark electricity price are calculated using the discounted cash flow method. Then, the graded electricity price is calculated according to the grade of the quality of grid-connected power. Finally, the ancillary service price is calculated based on the graded electricity price and ancillary service compensation. The case studies verify the validity of the three-part electricity price mechanism. The verification shows that the three-part electricity price mechanism can help PV-BESS power plants to obtain good economic returns, which can promote the development of PV-BESS power plants.

Keywords: PV-BESS power plants; three-part electricity price; capacity price; graded electricity price; ancillary service price

1. Introduction

With the increasingly severe problem of traditional fossil energy use and related environment impacts, environmental pollution control in China is focusing on energy saving, emission reduction, and green and low-carbon development. From the perspective of the carbon emissions structure in China, the carbon emissions of the electric power industry are growing rapidly, and the proportion is increasing annually [1,2]. Under the background of the low-carbon economic development, renewable energy is increasingly recognized in China, and a series of measures to promote renewable energy development has been adopted. Compared with conventional power generation, PV power generation has the advantages of being safe and clean and having abundant reserves. PV power plays a major role in renewable resources.

According to statistical analyses, China is one of the countries with abundant solar energy resources. In more than 2/3 of the total area of the country, the annual sunshine duration is more than 2000 h, and the annual radiation is more than 5000 MJ/m^2. The total amount of solar radiation received by the land area in China is 3.3×10^3–8.4×10^3 MJ/m^2, which is equivalent to the reserves of

2.4×10^4 million tons of standard coal [3]. According to relevant statistics, the total installed capacity of PV power generation in China had reached 77.4 GW by the end of 2016, which means China has become the country with the largest installed PV power generation capacity. With the further development of China's PV industry, the capacity of PV generation in China is expected to show an increasing trend in the next few years. It is predicted that the total installed capacity of PV generation in China will reach at least 105 million kW by 2020.

Currently, the PV industry is developing rapidly, but certain challenges still exist. For example, the increasingly serious problem of solar abandoning has still not been resolved. Solar abandoning occurs primarily in Gansu, Xinjiang and Qinghai in Northwest China. According to the National Bureau's statistical data for 2016, the solar abandoning rate was 30% in Gansu, 32% in Xinjiang, and 8.33% in Qinghai. This problem has had a severely adverse influence on PV power consumption and has led to a waste of solar energy resources. There are several reasons for occurrences of solar abandoning. First, the installed capacity of new power in north-west China has increased too fast as the growth rate of demand for electricity has slowed down. The construction of external transmission channels does not match the power supply, and the power transmission capability is limited. Second, large-scale PV power stations' access to the grid has a great impact on the network because of the fluctuation of PV power generation. To ensure the safety and stable operation of the grid, the capacity of grid-connected PV power generation has to be reduced. Compared with wind power, the density of solar energy is lower. PV energy comes from sunlight, so weather conditions affect the PV power generation output, which makes it difficult to control [4–7]. Therefore, certain requirements are proposed for energy storage equipment [8–12]. The installation of energy storage devices makes it easier to control PV output [13,14]. A solar energy storage power plant can not only effectively restrain the fluctuation of PV power output but also reduce the PV power amount and improve the utilization of solar energy resources.

According to an investigation and instruction by China's National Development and Reform Commission, a demonstration PV-BESS power plant has been constructed and placed into operation in July 2016 in Golmud of Qinghai Province. In the demonstration PV-BESS power plant, the capacity of PV generation units is 50 MW, the rated power of the energy storage system is 15 MW, and the rated capacity of the energy storage system is 18 MWh [15].

Commonly, the cost of a generating asset or the power system is evaluated using the levelized cost of electricity (LCOE) [16]. A new loan repayment method is proposed in [17] to analyse the generation cost of PV power plants in different regions. The cost and benefit of different types of energy storage systems are analyzed in detail in [18–21]. A new metric levelized cost of delivery (LCOD) is proposed to calculate the LCOE for the electrical energy storage in [22]. In [23], an innovative two-part feed-in tariff is proposed for renewable energy generation, which consists of capacity and market-based energy payments. The capacity payment is applied to ensure the power plants obtain basic income to recover their investment costs, while the market-based energy payment is applied to enable the power plants' participation in the competition, which can incentivize the power plant to reduce generation costs and improve generation efficiency. The principle that the interests of the relevant subjects remain static is applied to design the two-part electricity price in [24]. The adjustment coefficient of supply and demand, adjustment coefficient of unit availability, and capacity charge balance mechanism are introduced in [24].

Experts and scholars are also concerned by the power quality problems induced by PV power generation. For the power quality problems brought by grid-connected PV systems, corresponding evaluation methods are proposed. The evaluation method of fuzzy mathematics is employed to evaluate power quality in [25]. The fuzzy method can be used to assess the uncertain power quality problems by using imprecise power quality data. The analytic hierarchy process (AHP) is applied to power quality evaluation in [26]. The power quality problem of PV power generation systems is analyzed in a hierarchical way, and a multi-decision problem is decomposed into many components, which helps to solve many difficulties in power quality evaluation. In [27], a classification method of power quality disturbance based on the least squares support vector machine (SVM) is proposed, which has a fast training speed and high classification accuracy.

With the ability to provide ancillary services quickly and flexibly, the battery energy storage system has drawn considerable attention in the application of new energy grid connections [28–30]. In [31], the authors studied the suitability of extending frequency control to renewable energy sources (RES) units and integrating them with energy storage systems. The results show that not only can the energy storage system be used to control the frequency of distributed generation, but also the integration of a distributed generation system with an energy storage system can provide the frequency regulation service. A dynamic model is established to evaluate the value of a vanadium redox flow battery used for frequency regulation service in Texas in [32] In a study conducted by Sandia Laboratory, a detailed analysis of the potential benefits of energy storage systems in ancillary services has been conducted [33]. Taking the vanadium redox flow battery as an example, the benefits of energy storage systems for ancillary services are analyzed considering the difference of energy storage scale in [34].

To fully reflect the value of the PV-BESS power plants, improve their financial viability, and promote the improvement of power quality, a three-part electricity price mechanism based on a deep analysis of the construction and operation costs and the economic income of power generation and ancillary services is proposed in this paper. The power generation price is divided into three parts: capacity price, graded electricity price, and ancillary service price. The fixed cost of the BESS is recovered by the capacity price. The fixed and variable costs of PV systems and other parts are recovered by the graded electricity price based on power quality, which can enable the PV-BESS power plants to participate in market competition. Additional ancillary services revenue can be obtained by the ancillary service price.

The structure of this paper is as follows: In Section 2, the current photovoltaic power tariff mechanism and assessment mechanism in China are introduced, and then the current economic benefits of PV-BESS power plants are analyzed. In Section 3, the construction and operation costs of PV-BESS power plants are analyzed, and the design principle and implication of the three-part electricity price are introduced. Based on this, the economic benefits of PV-BESS power plants with the three-part electricity price are analyzed. In Section 4, the capacity price and benchmark electricity price are calculated based on the discounted cash flow method. In Section 5, the Analytic Hierarchy Process-Criteria Importance Though Intercriteria Correlation (AHP-CRITIC) method and improved Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) are employed to calculate the graded electricity price based on the benchmark electricity price. In Section 6, the ancillary services of the PV-BESS power plants are introduced, and then the electricity stored in the BESS for ancillary services are calculated by the simulation. Finally, the ancillary service price is analyzed. Sections 7 and 8 are the case studies and conclusions.

2. The Current PV Tariff and Assessment Mechanism and Economic Benefits of PV-BESS Power Plants in China

There is not yet a clearly defined price mechanism for the PV-BESS power plant in its initial development stage. The current PV tariff and assessment mechanism are applied to PV-BESS power plants.

2.1. The Current PV Tariff Mechanism

The current electricity price mechanism for the PV power plants is the stake electrovalence, which is divided into several levels according to the abundance of the solar resources. The PV stake electrovalence is the a tariff charged by a PV power plant when it sells electricity to a power grid company, and it is developed by the government based on the current cost of PV power generation and the consideration of reasonable profit. The PV stake electrovalence is applied to each resource zone according to the resource status and the generation cost. In the zone with the same type of solar resource abundance, the PV electricity price is the same. The classification standards of various resource zones and stake electrovalence in 2015–2017 are shown in Table 1.

Table 1. The Photovoltaic resource zones and stake electrovalence in 2015–2017.

Resource Zone	Annual Total Radiation (MJ/m^2)	Some Provinces	PV Stake Electrovalence (Yuan/kWh)		
			2015	2016	2017
Class I	6700–8370	Ningxia, Qinghai	0.9	0.8	0.55
Class II	5400–6700	Beijing, Tianjin	0.95	0.88	0.65
Class III	4200–5400	Shanghai, Zhejiang	1	0.98	0.42

2.2. The Current PV Assessment Mechanism

In addition to the PV stake electrovalence, there is an assessment mechanism for PV power generation, which is used to assess the PV power generation capacity, PV power output and power quality. The assessment standards vary in different resource zones. Take Northwest China, which is classified in class I, as an example, according to the management rules for the Grid Connecting and Auxiliary Service of Power Plants in the Northwest Region of China, the average absolute error in the short-term forecast of the PV power generation period, excluding the output-controlled period, should be less than 15%. If the error is greater than 15%, each increase of one percentage point will result in economic punishment of 2000 yuan/10^4 kW based on the total installed capacity of the plant. In the current PV assessment mechanism of China, the short-term forecast of the PV power is the day-ahead forecasting, which means the forecasting horizon is one day. And the forecasting interval is 15 m, which means there are 96 points in the forecasted PV output curve and actual measured PV output curve.

2.3. The Economic Benefits of PV-BESS Power Plants

With the current PV tariff and assessment mechanism, the economic benefits of PV-BESS power plants are divided into two parts: power generation income and assessment costs.

$$\begin{aligned} R &= R_{ELC} - C_{ASS} \\ &= \rho_s \cdot Q - \delta \cdot C \end{aligned} \tag{1}$$

where R is the economic benefits of a PV-BESS power plant, R_{ELC} is the power generation income (yuan), C_{ASS} is the assessment costs, ρ_s is the PV stake electrovalence (yuan/kWh), Q is the power generation energy (kWh), δ is the assessment coefficient (yuan/kW), C is the installed PV capacity (kW).

Under the current PV electricity price mechanism, it is very difficult for the PV-BESS power plants to survive and develop. Compared with the ordinary PV power plants, the energy storage system of PV and energy storage power plants requires a significant amount of capital investment. Therefore, a reasonable electricity price mechanism, which provides a reasonably higher price for the PV-BESS power plant with higher power quality, is conductive to guide the PV power plants to add energy storage systems actively. More importantly, it can contribute to the promotion and development of PV-BESS power plants.

3. Analysis of Economic Cost and Income of PV-BESS Power Plants Based on the Three-Part Electricity Price

3.1. Analysis of Economic Cost of PV-BESS Power Plants

3.1.1. Construction Costs

Construction costs include equipment purchase, installation costs, construction project costs and other expenses. The equipment purchase and installation costs comprise investments in the PV systems, i.e., energy storage systems and control systems. The construction project costs include the cost of the power generation equipment, housing construction, and road traffic projects. Other expenses include the costs of surveying and designing, and construction management fees. The construction costs are shown in Figure 1.

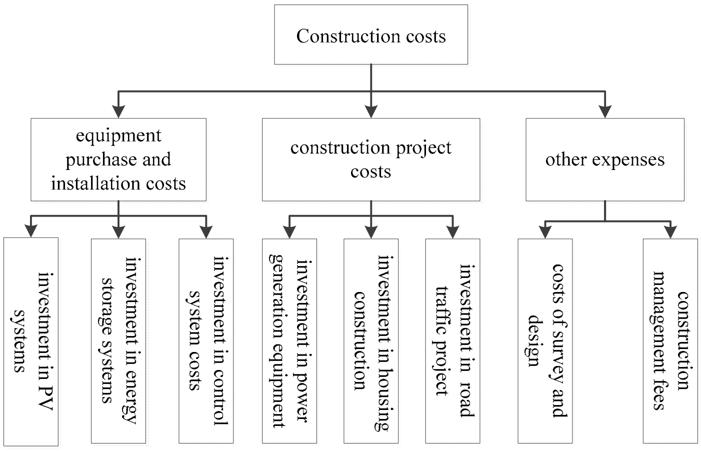

Figure 1. Construction costs of the photovoltaic-battery energy storage system (PV-BESS) power plants.

3.1.2. Operating Costs

The power generation of PV-BESS power plants primarily depends on sunlight, so its operating costs primarily include maintenance costs, wages and benefits, financial costs and sales expenses. Maintenance costs include the costs of equipment repair, equipment renewal, and equipment maintenance. Wages and benefits include wages, housing funding and insurance. The financial expenses are the principal repayment and interest repayment of long-term loans. The sales expenses are primarily sales income tax and amortization fees. The operating costs are shown in Figure 2.

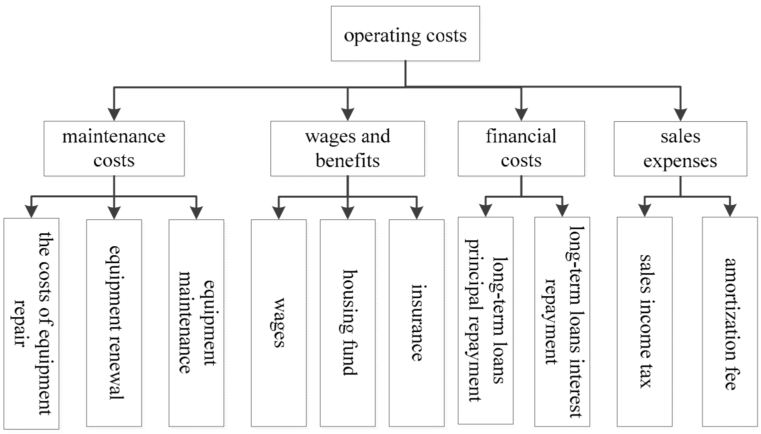

Figure 2. The operating costs of the PV-BESS power plants.

3.2. The Design Principle and Implication of the Three-Part Electricity Price

Through the analysis of the construction and operation costs of the PV-BESS power plants, the cost of power generation can be divided into two parts: the capacity cost of BESS and the energy cost of electricity. Between these, the capacity cost of BESS is primarily composed of the investment cost of BESS, while the energy cost of electricity is primarily composed of the investment cost of the PV power generation system and the operation cost of the whole PV-BESS power plant. To recover the cost of power generation and ensure a reasonable economic return and to take full advantage of the

BESS in improving the power quality and reliability of PV power generation, a three-part electricity price mechanism is proposed in this paper. The three parts are the capacity price, graded electricity price and ancillary service price.

The function of the capacity price is to recover the capacity cost of BESS. The function of the graded electricity price is to recover the energy cost of electricity and to guide the PV-BESS power plant to give full play to the role of the BESS in improving the power quality and reliability of PV power generation. The function of the ancillary service price is to reflect the value of the BESS in participating in the ancillary services. Further, the PV-BESS power plant can obtain additional economic income via the ancillary service price. Additionally, the ancillary service market in the electric power industry of China can be improved.

In summary, the basic structure of the three-part tariff is shown in Figure 3.

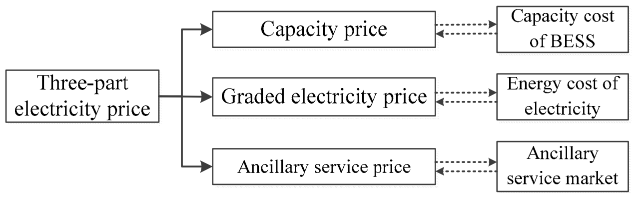

Figure 3. The basic structure of the three-part electricity price.

3.3. Analysis of Economic Income of PV-BESS Power Plants Based on the Three-Part Electricity Price

Under the three-part electricity price proposed in this paper, the economic benefit R of PV-BESS power plants in the n-th year of the operating period is primarily composed of four parts: the capacity charge, electricity charge, ancillary service income and rewards or punishments of assessment.

$$\begin{aligned} R &= R_C + R_E + R_A + R_{RE} \\ &= \rho_c \cdot C_{bess} + \rho_e' \cdot Q_e^n + \rho_a \cdot Q_a^n + \nu \cdot Q_e^n \\ &= \rho_c \cdot C_{bess} + \rho_e^0 \cdot (1+\mu) \cdot Q_e^n + \rho_a \cdot Q_a^n + \nu \cdot Q_e^n \end{aligned} \quad (2)$$

The variable R_C is the capacity charge, ρ_c is the capacity price (yuan/kWh), and C_{bess} is the rated capacity of the energy storage system (kWh).

The variable R_E is the electricity charge, ρ_e' is the graded electricity price, ρ_e^0 is the benchmark electricity price (yuan/kWh), μ is the adjustment coefficient of the benchmark electricity price (%), which is determined according to the PV power quality grade, and Q_e^n is the total power generation of the n-th year (kWh).

The variable R_A is the ancillary service income, ρ'_a is the ancillary service price (yuan/kWh), and Q_a^n is the energy stored by the battery energy storage system for ancillary services during the n-th year. A detailed description of this parameter is shown in Section 5.

The variable R_{RE} is the rewards or punishments of assessment and ν is the coefficient of rewards or punishment (yuan/kWh). R_{RE} is different as C_{ASS} in Equation (1), because if ν is greater than 0, R_{RE} refers to the economic reward of the assessment, otherwise it refers to the punishments of assessment. With the current assessment mechanism, C_{ASS} can only be the punishments of assessment.

The electricity charge is primarily used for the recovery of PV power generation systems and other parts of the fixed and variable costs. The energy storage system can realize the control of power quality by an appropriate inverter control strategy, which can help to improve the power quality of the grid-connected photovoltaic system. To promote the PV-BESS power plants to take full advantages of the energy storage systems, the electricity price is graded according to the power quality, and the principle of high quality and high price is established. A detailed description of the classification method for power quality is shown in Section 4. In this paper, the adjustment coefficients of the benchmark electricity price are set according to Table 2.

Table 2. Adjustment coefficients corresponding to different power quality grades.

Power Quality Grade	1	2	3	4	5
μ(%)	0	10	20	30	40

According to the detailed rules of the implementation of grid operation management for the north-west regional power plants in China, the power grid dispatch centre evaluates the monthly average absolute deviation between the actual grid connection and the 96-point value of the short-term forecast. If the deviation is too large, the PV power plants receive a certain economic punishment. The energy storage system is flexible and responsive, which can stabilize the fluctuation of PV power. According to the advantage of the energy storage system, the rewards or punishments are set up based on the existing assessment standards. The value of ν is set up according to the deviation between the actual grid-connected power and the forecasted value to encourage the construction of energy storage systems. In this paper, the coefficients of rewards and punishments are set according to Table 3.

Table 3. Coefficients of the rewards and punishments corresponding to different photovoltaic (PV) power deviations.

Power Deviation (%)	More than 25	20–25	15–20	10–15	5–10	0–5
ν (yuan/$\times 10^4$ kWh)	−100	−50	0	50	70	80

4. The Capacity Price and Benchmark Electricity Price Based on the Discounted Cash Flow Method

The discounted cash flow method [35] is a pricing method that focuses on the annual cash flow of electric power enterprises and ensures that the net cash flow of the power plant in the operating period can meet the prescribed capital internal rate. The discounted cash flow method can help guarantee a reasonable return on the investment in the operating period. The specific method is to adjust the electricity price in the case of a given internal rate of return, to meet the following equation [36]:

$$NPV = \sum_{n=0}^{N} \frac{CI_n - CO_n}{(1 + IRR)^n} = 0 \tag{3}$$

where NPV is the present value of net cash flow (10^4 yuan RMB), CI_n and CO_n are the cash inflow (10 k RMB) and cash outflow (10^4 yuan RMB) in the n-th year, respectively, $CI_n - CO_n$ is the net cash flow for the n-th year; IRR is the internal rate of return on the investment principal (%), which represents the discounted rate of the cumulative amount of the net cash flow of the power plant during the entire operation period; and N is the entire life cycle, including the project construction period (year).

The cash inflow includes the capacity charge, electricity charge, auxiliary service income and appraisal reward and rewards or punishments of assessment. According to Equation (2), the annual cash inflow can be expressed as:

$$CI_n = \rho_c^n \cdot C_{bess} + \rho_e^0 \cdot (1 + \mu) \cdot Q_e^n + \nu \cdot Q_e^n + \rho_a \cdot Q_a^n \tag{4}$$

When calculating the capacity price and the benchmark electricity price, the rewards or punishments of assessment and the adjustment of benchmark electricity price are not considered. Additionally, compared with the capacity and electricity charges, the ancillary services income amount is small. Moreover, to facilitate the calculation of the electricity price, the ancillary service price is excluded from the capacity price and the benchmark electricity price accounting.

Then, Equation (3) can be rewritten as:

$$\sum_{n=0}^{N} \frac{\rho_c^n \cdot C_{bess} + \rho_e^0 \cdot Q_n - CO_n}{(1+IRR)^n} = 0 \quad (5)$$

Equation (5) indicates that under the condition of the energy storage capacity, the annual electricity consumption and cash flow are given, and thus, the capacity price and the benchmark electricity price will remain the same during the entire power plant operation period. To ensure the investment of the PV-BESS power plant has the basic *IRR*, it is set as the industry average of 8% [37]. Thus, the capacity price is a function of the benchmark electricity price, which can be expressed as:

$$\rho_c = f\left(\rho_e^0\right) \quad (6)$$

The relationship of ρ_c and ρ_e^0 can be obtained according to Equation (5) and be briefly expressed by Equation (6). Since the fixed cost of the BESS is recovered by the capacity price ρ_c and the fixed and variable costs of PV systems and other parts are recovered by the benchmark electricity price ρ_e^0, therefore, once the ratio of the electrical capacity charge in the total economic income is determined, the capacity price ρ_c and the benchmark electricity price ρ_e^0 can also be obtained accordingly. In this paper, the ratio of the energy storage system cost to the total construction cost is set as the ratio of the electrical capacity charge to the total economic income.

5. The Graded Electricity Price Based on the AHP-CRITIC Method and Improved TOPSIS

According to the technical requirements of grid-connected PV power generation in China, the indexes of power quality employed in this paper include the voltage deviation, frequency deviation, voltage fluctuation, harmonic distortion rate and voltage three-phase unbalance degree. The AHP and the Criteria Importance Though Intercriteria Correlation (CRITIC) are combined to determine the weight of power quality for each index, and the improved Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is employed to classify the power samples into different grades according to their power quality.

The basic idea of the AHP [38–40] is to separate the problem into different component factors and assemble these factors in different hierarchies according to the interactive influence and affiliation relationship to form a multi-hierarchy analysis structure model. The CRITIC is an objective weighting method proposed by Diakoulaki [41]. The basic idea of CRITIC is that the objective weights of the indexes are determined based on the contrast intensity and conflicts between evaluation indexes. The basic principle of the TOPSIS is to sort the samples by measuring the distances between the evaluated object, the positive ideal solution and the negative ideal solution [42–45]. To overcome the he inverse problem of the method in power quality evaluation, the concept of the absolute positive ideal solution and absolute negative ideal solution in TOPSIS are introduced in this paper. The specified value of the power quality in the Guo Biao (GB) of China is regarded as the absolute positive ideal solution, and the limited value of the power quality in the GB of China is considered the absolute negative ideal solution.

The particular process of the power quality evaluation method based on the AHP-CRITIC and improved TOPSIS proposed in this paper is shown in Figure 4.

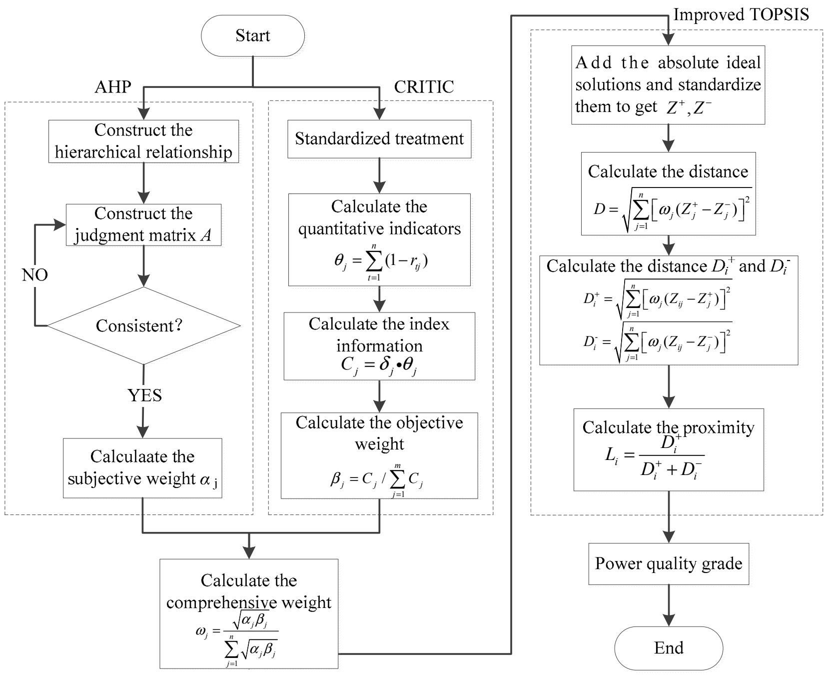

Figure 4. The flow chart of power quality analysis and evaluation.

In the flow chart above, r_{tj} is the relative coefficient between index t and j, δj is the standard deviation of the j-th evaluation index, $Z^+ = (Z_1^+, Z_2^+, \cdots Z_n^+)$ and $Z^- = (Z_1^-, Z_2^-, \cdots Z_n^-)$ are the absolute and negative ideal solutions, respectively, after the standardization.

The power quality is divided into five grades in this paper: level five/excellent ($0 \leq L_i < 0.25$), level four/good ($0.25 \leq L_i < 0.5$), level three/medium ($0.5 \leq L_i < 0.75$), level two/qualified ($0.75 \leq L_i \leq 1$), and level one/unqualified ($L_i > 1$).

According to the grade of the power quality, the benchmark electricity price can be adjusted to a certain extent by the adjustment coefficient μ to form the graded electricity price. The implementation of the graded electricity price is helpful to promote PV plants to give full play to the regulation and control of energy storage devices. The graded electricity price can be calculated by the formula below:

$$\rho_e' = \rho_e^0 \cdot (1 + \mu) \tag{7}$$

where ρ_e' is the graded electricity price. The adjustment coefficient μ depends on the grade of the power quality, and it can be determined by the power companies and power plants according to specific policies.

6. The Ancillary Service Price of the PV-BESS Power Plant

6.1. Analysis of the Ancillary Service of the BESS

An ancillary service refers to the peak regulation, frequency regulation, and standby and black start service, which ensures the system security, stable operation and power quality. Ancillary services are closely related to the electricity market.

In the current power system of China, the application technology of BESS is not mature enough and the ancillary services market is imperfect. So the ancillary services provided by the BESS are still in their infancy and have not yet been implemented for large-scale commercial applications. In 2016, the National Energy Administration of China issued the circular on the promotion of electric energy storage to participate in the "Three North" regional power ancillary services compensation (market) mechanism (State Regulation [2016] No. 164) to promote energy storage facilities of the power generation side to participate in peak shaving and frequency modulation auxiliary services [46].

The peak shaving auxiliary service means that the BESS charge during low load periods or solar abandoning periods, and discharge during other periods, which can contribute to Peak shaving and valley filling for the load of power grids. The frequency modulation auxiliary service means that when the frequency of the power grid fluctuates and deviates from the equilibrium point (50 Hz in China), through the rapid charging and discharging of the BESS, the output of other generators in the power system is compensated to make the frequency of the power grid reach the balance requirement. To facilitate the analysis, this paper takes the frequency modulation auxiliary service as an example to analyse the potential and economic benefits of the auxiliary power station [47].

The service of frequency modulation control means that [48] generating units provide adequate adjustment capacity and a certain rate of adjustment to meet the requirement of system frequency by way of dealing with the mismatch between a small load and the generation power in real time. The general frequency modulation function of the power system is primarily composed of the traditional power supply, such as hydro generating units, gas generating units, and coal-fired units. The Automatic Generation Control (AGC) frequency modulation's performance of these power supplies is still a gap compared with the expected adjustment of the grid, which is shown as the delay of the regulation and the deviation (overshoot and undershoot). The comparison of frequency modulation effect between energy storage and traditional power supplies are shown in Table 4.

Table 4. Comparison of the battery energy storage system (BESS) and conventional power supplies.

Unit Type	Gradeability (%/min)	Short-Term Gradeability Demand of the Grid (MW/min)	Total Power Demand of the Unit (MW)	Total Power Demand of the BESS (MW)	Substitution Effect of the BESS
Hydroelectric unit	30	10	33.33	20	1.67
Gas generator unit	20	10	50.00	20	2.50
Coal-fired unit	2	10	500.00	20	25.00

In Table 4, the unit type refers to the types of the generating units, and the gradeability refers to the ratio of the maximum adjusted output to the rated capacity of the system per minute, which reflects the frequency regulation ability of the generating units. The short-term gradeability demand of the grid is the frequency regulation demand of the grid. The total power demand of the unit is the demand of the different units for frequency regulation, and it can be calculated by the gradeability and the short-term gradeability demand of the grid. Take the hydroelectric unit in Table 4 as an example, the total power demand is calculated as 10/30% = 33.33 MW. The total power demand of the BESS is the demand of the BESS for frequency regulation in the same occasion. Finally, the substitution effect of the BESS refers to the substitution effect of the BESS on conventional units, e.g. the substitution effect of the BESS on hydroelectric unit is calculated as 33.33/20 = 1.67.

Table 4 shows that the urgency of the regulation of the system makes energy storage technologies more advantageous. The results of the study presented by the US Pacific Northwest National Laboratory show a precise conclusion through more complex simulations: The energy storage technology with a fast adjustment ability can more effectively provide frequency modulation services; according to the power characteristics of the California power market, the frequency modulation effect of energy storage is approximately 1.7 times of that of the hydroelectric generating unit, which is approximately 2.5 times of that of the gas turbine and more than 20 times of that of the coal-fired unit [49].

According to the current policy of ancillary service compensation in China, the price mechanism of coal-fired power generation units participating in ancillary services refers to the supplementary service compensation price per the original tariff. For example, the price of the coal-fired units in north-east China is RMB 0.386 yuan /kWh, and the compensation price for the auxiliary services is RMB 0.06 yuan (/kWh). Therefore, the tariff of the energy storage system for ancillary service can be expressed as the sum of the benchmark electricity price and compensation price for the ancillary service as follows:

$$\rho_a = \rho_e^0 + \rho_{asc} \tag{8}$$

where ρ_{asc} refers to the compensation price of the energy storage system for the ancillary service. Considering the investment cost of the energy storage system and the effect of frequency modulation, the compensation price of the energy storage system is five times that of the coal-fired power plant, that is to say, 0.3 yuan/kWh.

6.2. Calculation of Electricity Stored in the BESS for Ancillary Services in the PV-BESS Power Plant

The pure PV power plant with an energy storage system can stabilize the output power fluctuation of the PV system and reduce the deviation between the actual and the short-term forecasted power by the rapid adjustment of the energy storage system. If there is electricity that is supposed to be abandoned while the PV power curve is optimized, the electricity can be stored by the BESS for the auxiliary service. The process of optimizing the PV power curve with the BESS is simulated. By analysing the charging and discharging power curve of the BESS and its state of charge (SOC), the electricity stored by the BESS can be calculated. The system structure diagram of the PV-BESS power plant and schematic diagram of simulation are shown in Figures 5 and 6.

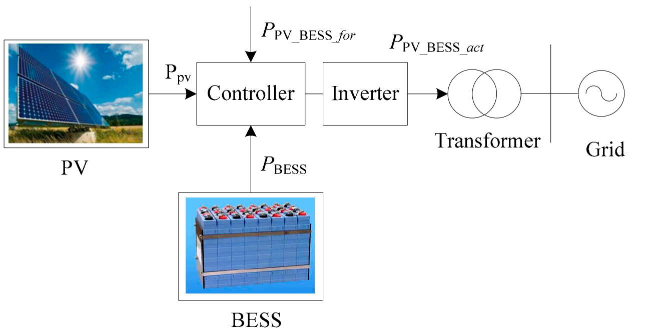

Figure 5. The system structure diagram of the PV-BESS power plant.

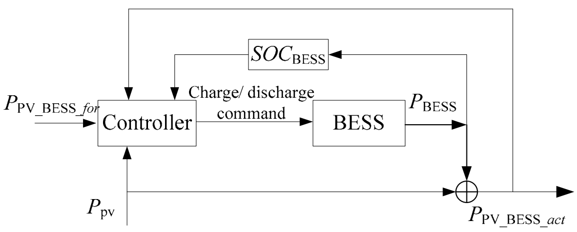

Figure 6. The schematic diagram of simulation.

The control strategy of the BESS to optimize the PV power curve is as follows:

(1) The objective of the optimization: the average absolute deviation of the actual power generation and short-term forecast value of the 96 points is less than the target value. That is:

$$\frac{|P_{\mathrm{PV\_BESS\_act}}(k) - P_{\mathrm{PV\_BESS\_for}}(k)|}{P_{\mathrm{pv\_BESS\_for}}(k)} \leq \delta \tag{9}$$

where $P_{\mathrm{PV\_BESS\_act}}$ (k) (k = 1, 2, . . . , 96) is the actual power of the PV-BESS power plant (MW), $P_{\mathrm{PV\_BESS\_for}}$ (k) (k = 1, 2, . . . , 96) is the forecasted power of the PV-BESS power plant (MW), and δ is the predetermined optimization objective (%).

(2) Constraint conditions:

a. The power balance constraint of the whole system

$$P_{PV} + P_{BESS} = P_{PV\_BESS\_act} \tag{10}$$

where P_{PV} is the power of PV system (MW) and P_{BESS} is the power of the BESS (MW).

b. The power constraint of the BESS

$$-P_{BESS\_rated} \leq P_{BESS} \leq P_{BESS\_rated} \tag{11}$$

where P_{BESS_rated} is the rated power of the BESS (MW).

c. The SOC constraint of the BESS

$$30\% \leq SOC_{BESS} \leq 100\% \tag{12}$$

where the SOC_{BESS} is the SOC of the BESS (%).

Take the demonstration PV-BESS power plant in Golmud of Qinghai Province in China as an example, in which the capacity of the PV generation units is 50 MW, the rated power of the energy storage system is 15 MW, and the rated capacity of the energy storage system is 18 MWh.

The output of the PV-BESS power plant is analyzed according to the four different seasons: spring, summer, autumn and winter, and the PV output of each season are divided into 5 types of typical days (a)–(e), as shown in Figure 7.

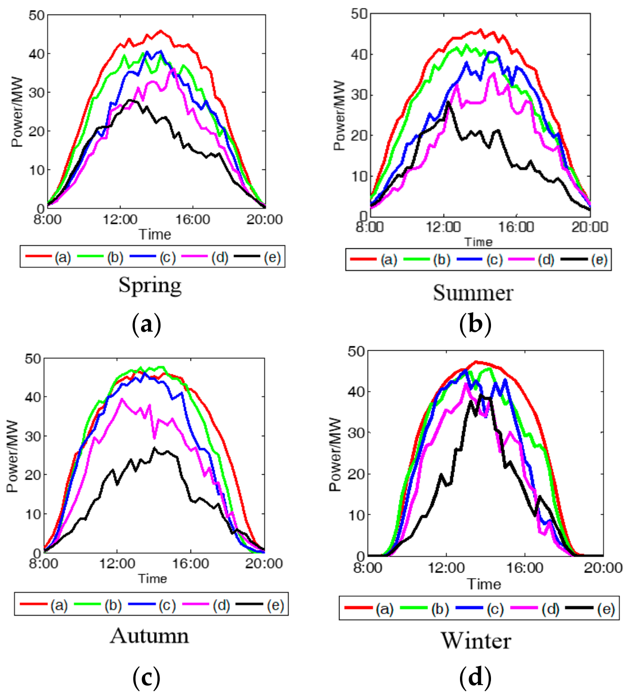

Figure 7. The PV output curves of 5 types of typical days in each season. (**a**) Spring; (**b**) Summer; (**c**) Autumn and (**d**) Winter.

The PV output curves of different types of typical days in each season reflect the influence of different weather conditions on the PV output to a certain extent. For example, the 5 types of typical days in summer correspond to sunny all day, sunny in the morning while cloudy in the afternoon, cloudy in the morning while sunny in the afternoon, cloudy all day and overcast all day. Since the simulation curves of different typical days are similar, only the simulation curves of typical day of (a) in winter is chosen as an example and the photovoltaic power generation is optimized to ensure the actual power generation and the short-term forecasted value of 96 points is less than 15%. The results are shown in Figures 8 and 9.

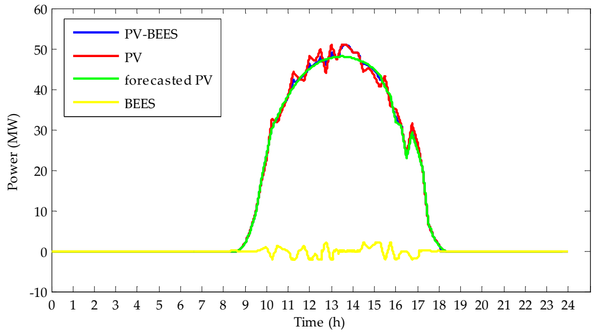

Figure 8. The PV power curve optimized by the BESS.

Since the dispatching instruction is based on the PV output forecasting, it can make the PV power output to track the scheduling instructions more accurate. Figures 8 and 9 show the energy storage system can be used to effectively optimize the power curve of PV power generation so that the deviation between the actual and the short-term forecast power curve can be effectively reduced. The larger the short-term fluctuation of PV power is, the larger the charging and discharging power of the energy storage system, and the higher the capacity requirement of the energy storage system. The simulation results in Figures 8 and 9 indicate that after the regulation of the BESS, the energy stored in the BESS is increased from 50% to 85%, which means that the energy stored in the BESS for ancillary services in typical day (a) in winter is about 35% of the total capacity of BESS.

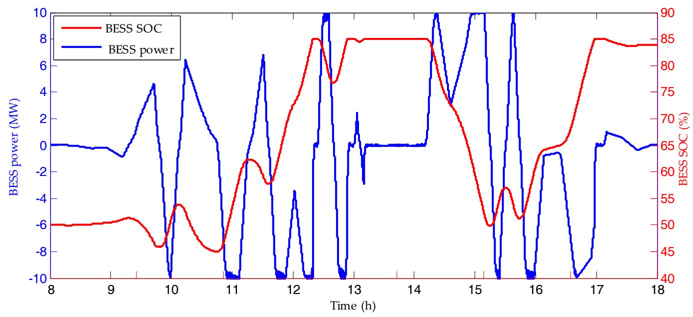

Figure 9. The charge-discharge power curve and state of charge (SOC) of the BESS.

Other typical days in each season are analyzed through the simulation to calculate the energy stored in the BESS for ancillary services, and the probability of each type of typical day and the change of the SOC of BESS (ΔSOC) are shown in Table 5.

Table 5. The probability of each type of typical day and the change of the SOC of BESS (ΔSOC).

Season	(a)		(b)		(c)		(d)		(e)	
	P	ΔSOC	P	ΔSOC	P	ΔSOC	P	ΔSOC	P	ΔSOC
Spring	26.6	41	23.3	35	15.0	36	15.0	31	20.0	30
Summer	28.4	43	22.2	36	19.7	35	13.5	32	16.0	28
Autumn	28.4	39	23.8	35	18.1	33	15.9	31	13.6	27
Winter	43.9	35	19.5	34	14.6	32	12.2	34	9.7	29

where (a)–(e) are the five types of typical days, P is the probability of the typical day (%), ΔSOC is the proportion of energy stored in the rated capacity of the BESS for auxiliary service (%).

The daily variation of the SOC of BESS can be $\Delta SOCav$ calculated by Equation (13):

$$\Delta SOC_{av} = \frac{1}{4}\sum_{i=1}^{4}\sum_{j=1}^{5} P_{ij}\Delta SOC_{ij} \tag{13}$$

where ΔSOC_{av} is the is the daily variation of the SOC of BESS (%), P_{ij} is the probability of the j-th typical day of i-th season (%), ΔSOC_{ij} is the change of the SOC of BESS in the j-th typical day of i-th season (%). i = 1, 2, 3, 4, j = 1, 2, 3, 4, 5.

Based on Table 5 and Equation (13), the ΔSOC_{av} can be calculated as 34%, which means the average daily energy stored in the BESS for ancillary services is about 34% of the rated capacity.

7. Case Studies

The basic data come from a demonstration PV-BESS power plant in Qinghai Province in China, in which the capacity of the PV generation units is 50 MW, the rated power of the energy storage system is 15 MW, and the rated capacity of the energy storage system is 18 MWh. In this paper, the three-part electricity price and the corresponding internal rate of return of a 50 MW PV power plant with different proportions of the battery energy storage system are studied. The rate of return under the existing electricity price mechanisms is taken as a comparison.

The designed service life of the demonstration PV-BESS power plant is 25 years. The annual equivalent available hours are 1578 h, and the annual generating capacity is approximately 78,915 MWh. The unit capacity cost of the battery energy storage system is 4.97 yuan/Wh. This capacity is 1.2 times the rated power of the energy storage system. Of the total investment in the plant, 70% is a bank loan with an equal principal repayment, a 15-year repayment period, and an annual interest rate of 6.55%. The plant is subsidized by the state in the first 20 years of operation, during which the electricity price is the PV stake electrovalence ρ_s 0.9 yuan/kWh. Moreover, the electricity price is the stake electrovalence of the coal-fired unit in Qinghai, which is 0.354 yuan/kWh. The income tax rate of the sales expenses is 25%. The specific data on the construction and operation periods of the demonstration PV-BESS power plant is shown in Table 6.

Table 6. The specific data on the construction and operation periods.

Period	Item	Amount ($\times 10^4$ yuan)
Construction	Investment of the PV system	33,878
	Investment of the energy storage system	4.97 yuan/Wh
	Other expenses	3235
Operation	Annual operating maintenance cost (2%)	995
	Annual repayment of the loan principal	2322.83
	Annual repayment of the loan interest	$34{,}842.5 \times (16 - n)/16$ ($n = 1, 2, \ldots, 15$)

7.1. Calculation of the Capacity Price and the Benchmark Electricity Price

Based on the data above, the capacity price and the benchmark electricity price under the condition of different BESS capacities can be calculated by the discounted cash flow pricing method. To ensure the PV-BESS power plant recovers the investment cost in the operation period, the *IRR* is set as the industry average of 8%. Since the BESS consists of many battery packs, the proportional relation between power and capacity of BESS is certain. So the rated power and capacity of the BESS unit can be determined according to the proportion of BESS. The capacity price and the benchmark electricity price of different BESS in the PV-BESS power plant are calculated. The specific calculation results of different proportions of BESS are shown in Table 7, Figures 10 and 11.

Table 7. The capacity price and the benchmark electricity price with different proportions of BESS.

Proportion of BESS (%)	The BESS Unit		Capacity Price (yuan/kWh·a)	Capacity Charge ($\times 10^4$ yuan/a)	Benchmark Electricity Price (yuan/kWh)	Benchmark Electricity Charge ($\times 10^4$ yuan/a)	Equivalent Single Price (yuan/kWh)
	Power (MW)	Capacity (MWh)					
0	0	0	0	0	0.7145	5638.5	0.7145
10	5	6	746.2644	447.7	0.7019	5539.0	0.7587
20	10	12	734.7575	881.7	0.6911	5453.8	0.8028
30	15	18	724.7478	1304.5	0.6871	5422.2	0.8470
40	20	24	715.9609	1718.3	0.6734	5314.1	0.8912
50	25	30	708.1857	2124.6	0.6661	5256.5	0.9353

where the proportion of BESS is the ratio of the BESS rated power to the PV rated power, the equivalent single price is the comprehensive price of capacity price and the benchmark electricity price, which is chosen as a contrast.

Figure 10 indicates that in the price aspect, with the increase of the capacity of the energy storage system, the equivalent single electricity price gradually increased, while the capacity price and benchmark electricity price gradually decreased. Figure 11 indicates that with the increase of the energy storage capacity, the investment cost gradually increased. To ensure the benchmark internal rate of return (8%) of the industry, the annual total electricity income increased gradually. The average annual capacity charge increased gradually, while the average annual benchmark electricity charge gradually decreased. The different trends in price and charge were caused by the relationship between the electricity charge, on-grid electricity and the electricity price.

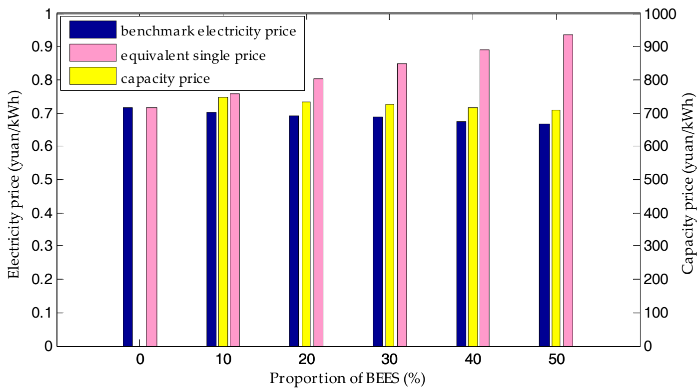

Figure 10. Comparison of the electricity price of the 50 MW PV plant with different proportions of BESS.

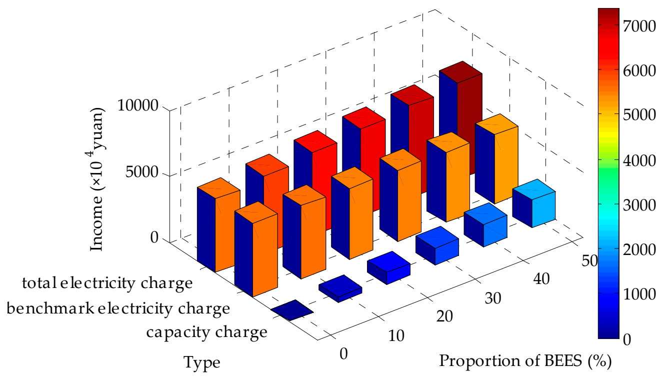

Figure 11. Comparison of the capacity charge and the benchmark electricity charge of the 50 MW PV plant with different proportions of energy storage.

7.2. Sampling Data of Power Quality Indexes and Power Quality Evaluation

The quality of the on-grid electricity of the PV power generation system is evaluated according to the comprehensive evaluation method proposed in this paper. The basic data of each index are from [50], which is the actual data measured at the grid connection point of the PV power generation system. The sample data of power quality indexes are shown in Table 8.

Table 8. The sample data of power quality indexes.

Index Sample	Voltage Deviation/%	Frequency Deviation/Hz	Harmonic/%	Voltage Fluctuation/%	Voltage Unbalance/%
1	3.212	0.0922	1.72	1.33	0.83
2	6.68	0.1562	4.28	1.53	1.36
3	4.35	0.118	2.67	1.95	1.35
4	5.33	0.1787	3.36	1.37	1.74
5	4.22	0.1892	4.57	1.58	1.83

The subjective weight calculated by the AHP is α = (0.1844, 0.1603, 0.4589, 0.1844, 0.0660). The objective weight calculated by the CRITIC is β = (0.2039, 0.1640, 0.1442, 0.3362, 0.1517). The comprehensive weight calculated by the Lagrangian Method is ω = (0.2080, 0.1416, 0.2759, 0.2671, 0.1074). The closeness of the evaluated object and the absolute ideal solution calculated by the improved TOPSIS is L = (0.6624, 0.7586, 0.8397, 0.8660, 0.9515). The evaluation result is shown in Table 9.

Table 9. The results of the power quality evaluation.

Sample	1	2	3	4	5
Grade	Level 3/medium	Level 4/qualified	Level 4/qualified	Level 4/qualified	Level 4/qualified

The results show that most of the evaluated samples of the power quality of grid-connected PV power plants without energy storage systems are at level 4/qualified and a few are at level 3/medium, which indicates that there is much room for the power quality to be improved.

7.3. The Comparison of the IRR of the PV-BESS Power Plant with the Three-Part Electricity Price and Current Stake Electrovalence

When the PV-BESS power plant is placed into operation, it will be involved in the assessment of the power grid dispatch centre, and the graded electricity price will be implemented. Based on the results in Table 7, the rewards or punishments of assessment of the PV plant with different capacities of energy storage systems is first calculated according to the adjustment coefficient of the benchmark electricity price and the coefficient of rewards or punishment. Then, the ancillary service income is calculated according to the simulation results. Next, the graded electricity price and electricity charge of the different levels of the grid connected power quality are calculated. Finally, the total economic income and expected internal rate of return (IRR) and investment payoff period (IPP) are calculated and compared with those of the current PV benchmark electricity price. The results are shown in Table 10, Figures 12 and 13.

Table 10. The comparison of the economic income and internal rate of return (IRR) of the 50 MW PV plant with different capacities of energy storage systems.

Proportion of BESS (%)	R_{RE} ($\times 10^4$ yuan/a)	R_C ($\times 10^4$ yuan/a)	R_A ($\times 10^4$ yuan/a)	Power Quality Grade	ρ_e' (yuan/kWh)	R_E ($\times 10^4$ yuan/a)	Three-Part Electricity Price		Stake Electrovalence (%)	
							IRR (%)	IPP (year)	IRR (%)	IPP (year)
0	−78.9	-	-	1 2	0.715 0.786	5638.5 6202.7	7.61 10.35	14.7 11.8	14.06	8.5
10	−39.4	447.8	27.3	1 2	0.702 0.772	5539.0 6093.0	10.30 12.84	12.5 11.6	11.71	10.1
20	0	881.7	54.2	2 3	0.829 0.898	6544.4 7089.7	12.59 14.97	11.5 8.9	9.70	11.9
30	39.4	1304.5	80.9	3 4	0.893 0.962	7048.7 7590.8	14.63 16.91	9.1 6.9	7.11	13.9
40	55.2	1718.3	106.4	4 5	0.875 0.943	6908.2 7440.1	14.15 16.22	8.4 7.3	6.45	15.4
50	63.1	2124.6	132.0	4 5	0.866 0.933	6833.2 7358.8	13.75 15.66	9.5 7.9	5.11	16.4

The following conclusions can be drawn from the above case studies:

(1) With the assessment of the power grid, the *IRR* with the current benchmark electricity price is gradually decreased with the increase of the capacity of the energy storage, which is due to the increase in the investment in energy storage systems and reflects the lack of the current benchmark electricity price.

(2) With the three-part electricity price proposed in this paper, the *IRR* of the PV plant is gradually increased and then gradually decreased after reaching the peak value with the increase of the capacity of the energy storage systems.

(3) When the 50 MW PV plant is equipped with the BESS of 15 MW/18 MWh, and the power quality grade is level 5/excellent, the capacity price is 724.7478 yuan/(kWh·a), the graded electricity price is 0.9619 yuan/kWh, and the ancillary service price is 1.2619 yuan/kWh. The investment would receive the maximum *IRR* of 16.91%. However, under the current PV stake electrovalence, the *IRR* is 7.11%, which is lower than the industry standard 8%.

(4) If the 50 MW PV power plant is not equipped with the BESS, the *IRR* is 14.06% with the current PV stake electrovalence 0.9 yuan/kWh. While with the three-part electricity price proposed in this paper, the *IRR* of the PV-BESS power plant equipped with BESS of 15 MW/18 MWh is 16.91%. The result indicates that the three-part electricity price can effectively promote the development of the PV-BESS power plants.

(5) When the proportion of BESS is high, which means that the investment costs of BESS is great, the three-part price proposed in this paper can effectively shorten the payback period of investment of the PV-BESS power plant. For example, when the PV plant is equipped with the BESS of 15 MW/18 MWh, as the demonstration PV-BESS power plant in Qinghai, the investment would receive the maximum IPP under the three-part price of 6.9 years, while the IPP is 13.9 years under the current PV stake electrovalence.

(6) When the BESS is 15 MW/18 MWh, both the IRR and IPP are optimal. So under the three-part price proposed in this paper, the economic efficiency of the PV-BESS power plant is optimal when the power plant is equipped with BESS of 15 MW/18 MWh.

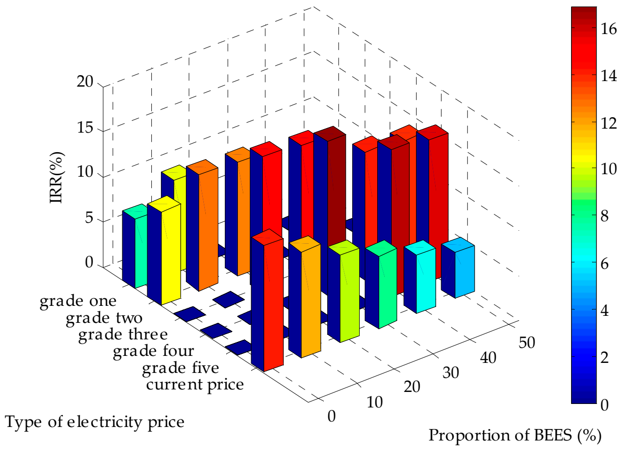

Figure 12. The comparison of the IRR with the three-part electricity price and the current stake electrovalence.

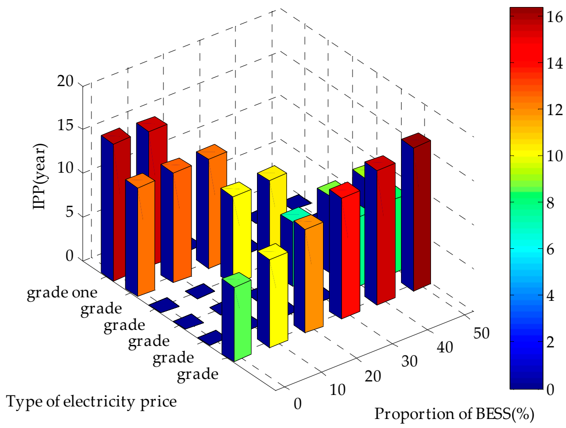

Figure 13. The comparison of the IPP with the three-part electricity price and the current stake electrovalence.

8. Conclusions

Large-scale energy storage systems can make a greater contribution to the promotion of PV energy consumption and the improvement of the quality of PV power. Presently, the development of PV-BESS power plants in China is still in its infancy. To protect the financial viability and promote the construction and development of the PV-BESS power plants, a three-part electricity price mechanism has been proposed in this paper based on a deep analysis of construction and operating costs and major economic incomes. The case studies indicate that with the three-part electricity price, the investment of PV-BESS power plants would receive good economic returns. As a result, the three-part electricity price can promote the construction of PV-BESS power plants and provide a reference for the commercial development of PV-BESS power plants in the future.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

PV	Photovoltaic
BESS	Battery energy storage system
AHP	Analytic hierarchy process
CRITIC	Criteria Importance Though Intercriteria Correlation
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
IRR	Internal rate of return
SOC	State of Charge

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