sustainability

MDPI

Article

Energy Storage Economic Analysis of Multi-Application Scenarios in an Electricity Market: A Case Study of China

Zhixian Wang [1], Ying Wang [1,*], Qia Ding [2], Chen Wang [1] and Kaifeng Zhang [1]

1 Key Laboratory of Measurement and Control of Complex Systems of Engineering, Ministry of Education, Southeast University, Nanjing 210096, China; zhixianwang@seu.edu.cn (Z.W.); wangchen1073@126.com (C.W.); kaifengzhang@seu.edu.cn (K.Z.)

2 NARI Technology Limited Company, Nanjing 211106, China; dingqia@sgepri.sgcc.com.cn

* Correspondence: wyseu@seu.edu.cn

Received: 24 July 2020; Accepted: 16 October 2020; Published: 20 October 2020

check for updates

Abstract: Energy storage has attracted more and more attention for its advantages in ensuring system safety and improving renewable generation integration. In the context of China's electricity market restructuring, the economic analysis, including the cost and benefit analysis, of the energy storage with multi-applications is urgent for the market policy design in China. This paper uses an income statement based on the energy storage cost–benefit model to analyze the economic benefits of energy storage under multi-application scenarios (capacity, energy, and frequency regulation markets) in China's future electricity market. The results show that the economic benefits of energy storage can be improved by joining in the capacity market (if it exists in the future) and increasing participation in the frequency regulation market. Nevertheless, the benefits under multi-application scenarios can hardly guarantee the cost recovery of energy storage under the current market mechanism or at the current price levels. Moreover, the economic benefits under different subsidy policies are studied, and the results show that energy storage can recover the cost with appropriate subsidy policies (the subsidy of 0.071 USD/kWh for pumped storage power stations is sufficient while the subsidy of 0.142 USD/kWh is required for electrochemical power stations). Finally, the sensitivity analysis of an energy storage power station to different price levels is carried out considering the difference in electricity price between China and the United States.

Keywords: energy storage; electricity market; cost–benefit analysis; multi-application scenarios

1. Introduction

Traditional coal resources produce a large amount of atmospheric carbon dioxide in the combustion process, which has adverse effects on climate change [1] and leads to a transformation of traditional energy structure. Renewable energy, represented by wind power and photovoltaics, is one of the substitutes for fossil fuel. Under the support of relevant policies issued by various countries, the proportion of renewable energy in power generation resources has steadily increased [2,3]. By the end of 2018, the installed capacity of renewable energy in China accounted for 18.9% of the total installed capacity. However, with the increasing penetration rate of renewable energy generation, the intermittency, volatility, and randomness caused by the external environment and weather also pose new challenges for the power grid [4]. In order to meet the characteristics of renewable energy, large-scale energy storage technology with excellent charge and discharge performance has attracted more attention and research [5]. The combination of energy storage and renewable energy can not only smooth the renewable energy's output, but also avoid the phenomenon of abandoning wind and solar to improve the utilization rate of renewable energy [6–8]. In addition, unexpected power imbalances will cause frequency instability [9]. Flexible start and stop ability and fast response make energy storage an increasingly important part of frequency regulation, which can be used as a key means of security protection [10–12].

Energy storage includes pumped storage, battery storage, flywheel storage, compressed air storage, and so on [13]. Recently, many scholars have studied the cost–benefit analysis of different energy storage technologies. Zhou et al. proposed an improved probabilistic production simulation method to assess the cost–benefit of pumped storage [14], and Guo et al. analyzed the life-circle sustainability of pumped storage from economic, social, and other indicators [15]. Correspondingly, Li et al. proposed a new cost–benefit model from the life-cycle perspective of battery energy storage in an energy island [16]. For different application scenarios, reference [17] calculated the costs and benefits of battery energy storage for reducing peak load in a medium voltage distribution network, and the authors of [18–20] verified the economic feasibility of batteries in peak valley arbitrage. Similarly, several authors have studied the cost–benefit analysis of compressed air energy storage [20], flywheel energy storage [21], and thermal energy storage [22].

At present, the cost–benefit analysis of energy storage in the literature is mostly based on the specific application scenario of a certain type of energy storage. Energy arbitrage, as the main source of income from energy storage, is often used as the benefit model to analyze the profits of energy storage [23]. However, the economic benefits of energy storage are not limited to this. Current energy storage applications mainly include helping the black start (the self-recovery of the power system after a large-scale blackout), cooperating with renewable energy, assisting in frequency adjustment or voltage support, providing capacity for grid reserve, supporting transmission, relieving the transmission congestion, etc. [24–26]. The wide application of energy storage allows it to participate in various markets and obtain profits flexibly, but the current research on the cost–benefit model hardly analyzes the economic situation of energy storage from the perspective of a market mechanism. The authors of [27] analyze the economic situation of energy storage in three main application scenarios (bulk energy storage, T&D support service, frequency regulation), but it is not connected with the electricity market. Although the authors of [21] consider that energy storage can obtain profits jointly in the energy market and auxiliary service market, they ignore the application of energy storage in the increasingly important capacity market. In addition, the income statement has been widely used as an important tool to analyze the economic benefits of enterprises, but it has not yet been used for energy storage economic analysis. Therefore, we establish a cost–benefit model under multi-application scenarios, which takes the simultaneous participation of energy storage in the three sub-markets (energy market, capacity market, and frequency regulation market) into account, and uses the income statement based on the proposed model to analyze the economic benefits of energy storage.

Meanwhile, China is currently implementing electricity market reform, so clarifying the cost–benefit model of energy storage in China's future electricity market plays an important role in guiding the construction and development of energy storage power stations. Among different energy storage technologies, pumped storage is the most mature and widely used energy storage technology [28]. By the end of 2018, China's pumped storage capacity reached 29.99 GW, accounting for 96% of the total installed capacity of energy storage. However, the development of pumped storage power stations is restricted by their geographical location, and now electrochemical energy storage (including lithium-ion battery, liquid flow battery, etc.) is the fastest-growing energy storage technology. In this paper, the above two kinds of energy storage technologies are selected as examples to calculate the cost and economic benefits of energy storage in China's future electricity market, and the main contributions are as follows:

(1) This paper proposes a cost–benefit model under multi-application scenarios based on the different mechanisms of energy market, capacity market, and frequency regulation market.
(2) This paper applies the proposed cost–benefit model to the income statement and selects two typical power stations to analyze the cost and economic benefits of energy storage under multi-application scenarios (capacity, energy, and frequency regulation markets) in China's future

electricity market. The two selected power stations are Yixing Pumped Storage Power Station and Zhenjiang Electrochemical Power Station.

(3) This paper compares the profits of energy storage under different market participations and subsidy policies, in consideration of the power stations' independent choice of markets and strong government support for the development of energy storage.

(4) This paper analyzes the sensitivity of energy storage power stations to different price levels, considering the difference of price between China's electricity market and the Pennsylvania-New Jersey-Maryland (PJM) market.

2. Energy Storage Cost Estimation under Multi-Application Scenarios

To analyze the energy storage economy under multi-application scenarios, it is necessary to establish cost and benefit models of energy storage first. Based on the investment-related cost model and the operational cost model of different applications in the literature [29], we expand it from a separate-single-application to multi-application cost model. Meanwhile, we consider more kinds of costs (such as financial expenses) of the energy storage system. In this paper, the cost of energy storage is divided into three categories, namely the investment cost, the operating cost in the markets, and other costs. The remaining parts of this section elaborate on these three kinds of costs, respectively, and the benefits model is introduced in the next section.

It should be noted that this article considers economic benefits from the perspective of the energy storage power station itself. When considering the cost and benefits of energy storage, the potential value of energy storage to the externalities can also be analyzed. However, it is difficult to directly realize the environmental benefits in China. Therefore, this paper does not consider the impact of energy storage on the externalities.

2.1. Investment Cost

As a fixed cost to be paid at the initial stage of the project construction, the investment cost is determined by the type and scale of the energy storage power station. For different types of energy storage, the initial investment varies greatly. At present, the investment cost of a pumped storage power station is about 878–937 million USD/GW, which is far higher than that of a battery storage power station, and is closely related to location. For battery energy storage, the initial cost mainly depends on different materials. Among them, the lead-carbon battery system is the lowest (about 139–183 thousand USD/MWh). As the most widely used type of battery, the cost of lithium-ion batteries has dropped significantly in the past few years, from 673–878 thousand USD/MWh to 146–219 thousand USD/MWh (here is the unit cost of lithium-ion batteries) [30]. Although the initial investment cost of a pumped storage power station is very high, this energy storage technology does not have the problem of battery component depreciation and the limitation of charging and discharging times, so it has long service life and low maintenance costs.

In this paper, we do not specifically calculate the initial cost of the power station, but directly give the total initial investment of each power station, denoted as $C_{Investment}$.

In general, the initial cost of an energy storage power station mainly includes the investment cost of the energy storage unit, power conversion unit, and other investment costs such as labor and service costs for initial installation. The specific calculations of these three parts used the formulas in Appendix 2 of literature [29].

This part of the cost ($C_{Investment}$) will be included in the specific calculation as "depreciation and amortization expense" when analyzing the economy of energy storage by using the income statement. Therefore, the initial cost is dispersed to each year. The specific calculation is as Equation (1):

$$C_A = \left(C_{Investment} - R_{StorageSystem}\right)/T_{life} \tag{1}$$

where C_A represents the annual depreciation and amortization expense costs used in the income statement (USD/year); $R_{StorageSystem}$ denotes the residual value of the energy storage system (USD); and T_{life} is the operating life of the energy storage system (year).

2.2. Operating Cost in Electricity Market

When energy storage participates in the electricity market, there are also operating costs. In the energy market and frequency regulation market, energy storage is in the process of continuous charging and discharging. In calculating this part of the cost, we should first consider the efficiency loss and self-discharge loss of the energy technology, which together determine the utilization efficiency of the energy storage system. At the same time, the operating cost is also affected by the current price in the energy and frequency regulation market, which is very complex. We synthesize this part of the cost and call it the charging cost of energy storage in the electricity market. This part of the calculation results will also be applied to the subsequent income statement.

Here we use "cost-of-service" [29] as the tool to calculate the charging cost of various energy storage technologies. This computing tool, which is calculated in the Excel platform, aims to provide the current and future charging costs of various energy storage technologies under multi-application scenarios (energy market, frequency regulation market, and capacity market). Since the unit cost is calculated here, we need to convert it into the charging cost of the entire power station and record it as $C_{Charging}$.

It is worth noting that due to the particularity of the capacity market, the energy storage does not need to bear additional charging costs when joining in the capacity market.

2.3. Other Costs

For the energy storage power station, there are still other costs that should be considered. First of all, the energy storage unit and energy conversion unit need regular maintenance and repair to ensure the normal operation of power equipment, which is an important daily expense. Secondly, due to the large initial investment of the energy storage power station (especially for the pumped storage power station), many power stations will require loans from a bank during the construction, so the relevant financial costs should be considered. Besides, there are some other costs collectively referred to as additional costs, which will not be detailed here. Here, we use C_M to represent maintenance cost and C_F to represent financial expense.

Due to the different conditions of each power station, the cost of this part varies greatly. In the subsequent economic analysis of energy storage through the income statement, it is treated with specific cases.

3. Energy Storage Benefit Estimation under Multi-Application Scenarios

This paper mainly analyzes the energy storage economy in the electricity market, so the following estimation starts from the three sub-markets of the electricity market. Combined with the specific application of energy storage, the benefit estimation model of energy storage power stations is proposed.

3.1. Benefit in Capacity Market

The capacity market encourages the construction of generating units by allowing reliable generating units (or equivalent demand response load) to obtain stable economic income outside the other two markets (energy market and auxiliary service market) with high uncertainty, so as to ensure the systems have sufficient generation capacity redundancy in the face of peak load. As the electricity market in China is still in the development stage, there have not been any relevant policies issued for the capacity market. Therefore, in this section, the benefit of energy storage in the capacity market is calculated by referring to the participation criteria used in the Pennsylvania-New Jersey-Maryland (PJM) electricity market of the United States.

The PJM capacity market consists of one base residual auction and three incremental auctions. Among them, the base residual auction holds capacity trading three years in advance. The first and third incremental auctions are used to let the seller purchase capacity to replace the capacity that cannot be performed. The second incremental auction carries out load forecasting again, and determines whether to make up the difference according to the gap between the load forecasting value and the previous one.

Equation (2) shows the annual revenue of the energy storage participating in the capacity market, which depends on the different capacity prices and the capacity of power stations. The relevant data used in the calculation of this paper are shown in Section 5.1.

$$E_{Capacity} = C_{station} \times P_{Capacity} \times T_y \tag{2}$$

where $E_{Capacity}$ is the annual revenue of the energy storage participating in the capacity market (USD/year); $C_{station}$ is the capacity of the energy storage power station (MW); $P_{Capacity}$ is the clearing price of the capacity market (USD/MW/day); and T_y is 365.

3.2. Benefit in Energy Market

In the energy market, energy storage stations gain profits through peak-valley arbitrage. That is, the energy storage system stores electricity during low electricity price periods and discharges it during high electricity price periods. Obviously, when there is a big gap between peak and valley price, energy storage stations can achieve better benefits, but when there is a slight difference between peak and valley price, energy storage stations need to consider other income methods. Similarly, Equation (3) calculates the one-year income of the energy storage power station participating in the energy market.

$$E_{energy} = C_{station} \times \left(P_{peak} \times T_{discharge} - P_{valley} \times T_{charge}\right) \times T_y \tag{3}$$

where E_{energy} is the annual revenue of the energy storage participating in the energy market (USD/year); P_{peak} is the average price of electricity in the peak period (USD); P_{valley} is the average price of electricity in the valley period (USD); and $T_{discharge}$, T_{charge} represent charge and discharge time, respectively.

3.3. Benefit in Ancillary Services Market

In the auxiliary service market, energy storage can participate in the reserve market (rotating reserve market and non-rotating reserve market) and frequency regulation market. According to the market clearing-price of auxiliary services provided by the PJM, the prices of rotating reserves and non-rotating reserves are very low. At the same time, compared with other power types, energy storage has a very fast response to frequency and can quickly track frequency changes to obtain better frequency regulation effects. Therefore, the frequency regulation market has always been one of the most important application fields of energy storage. Considering the above factors, this paper mainly considers the benefits of energy storage in the frequency regulation market, that is, to obtain income by providing auxiliary frequency regulation services. The specific calculation formula for the annual income of energy storage in the frequency market is Equation (4):

$$E_{regulation} = C_{station} \times P_{regulation} \times T_{regulation} \times T_y \tag{4}$$

where $E_{regulation}$ is the annual revenue of the energy storage participating in the frequency regulation market (USD/year); $P_{regulation}$ is the service price in the regulation market (USD); and $T_{regulation}$ is the time in which storage systems participate in the regulation market every day.

$$E_{Total} = E_{Capacity} + E_{energy} + E_{regulation} \tag{5}$$

The total income of the energy storage power station in the electricity market is the sum of the three submarkets, as in Equation (5). Since the energy storage station can choose whether to participate in the capacity market or not, as well as whether to participate in the energy and frequency regulation markets in different proportions, there is a certain floating space for its income.

4. Economic Analysis Method of Energy Storage under Multi-Application Scenarios

4.1. Income Statement Based on Cost–Benefit Estimation

For any enterprise, profit is the basic requirement of its development. Companies evaluate their profitability by analyzing the cost–benefit situation of each stage, and change their profit structure or put forward relevant policies. As a strategic energy source, energy storage economic analysis has an important impact on the prospects of the energy storage industry, and can also provide guidance for its development.

The income statement is an accounting statement that reflects the operating results of an enterprise within a certain period of time, which can directly reflect the profit situation of the enterprise and specifies the formation process of the profit from the calculation process. The formation of the income statement can be divided into the following four steps.

First of all, without subsidies, the total sales revenue of the energy storage power station after participating in the three markets, minus the total charging cost, the corresponding value-added tax (VAT), and the maintenance costs gives the product sales profit, which can be expressed by Equation (6):

$$M_{Sale} = E_{Total} - C_{Charging} - VAT - C_M \tag{6}$$

where $VAT = \left(E_{Total} - C_{Charging}\right) * 17\%$

The second step is to deduct the depreciation and amortization expenses from the sales profit to determine the profit before interest and tax (income tax) as in Equation (7). The annual depreciation and amortization expenses are calculated by dividing the initial investment minus the recovered capital into each year.

$$M_{Before} = M_{Sale} - C_A \tag{7}$$

The third step is to consider financial expenses on this basis. The financial cost is the interest on bank loans. If the initial investment of the power station includes the loan part, we need to add this part of the cost in our calculations. Finally, the net profit of the power station can be obtained by subtracting the income tax, as shown in Equation (8).

$$NP = M_{Before} - C_F - Income\_tax \tag{8}$$

where $Income\_tax = M_{Before} * 25\%$ (If the cost of the power station cannot be fully recovered, i.e., $M_{Before} < 0$, the income tax is zero).

In this article, the innovation is to integrate the cost and benefit estimation model under multi-application scenarios into the income statement to analyze the economic situation of the energy storage power station.

4.2. Economic Analysis Indicators

In this paper, we use two indicators to evaluate the economy of energy storage:

(1) Net profit: Net profit is the final income of the power station after the removal of various costs and other expenses. It reveals whether the energy storage power station can make profits, thus, it is an important indicator to measure the economic situation of energy storage power stations. It can be obtained directly through the income statement.

(2) Internal rate of return (IRR): When evaluating economic benefits, the time value of money should also be considered. Internal rate of return (IRR) is the discount rate when the total amount of

expenses and income flows are equal under the condition of considering time value. Net present value (NPV) is the conversion of future income to the present when a discount rate is given. Thus, IRR also refers to the discount rate when the cumulative NPV is 0. For an investment project, IRR is the rate of the largest currency depreciation that the project can withstand, so it is always used to indicate whether it is worth investing in the project. Usually, the larger the IRR, the better the return.

By definition, when Equation (9) equals to zero, IRR can be calculated accordingly [31]. In this article, IRR is calculated by EXCEL.

$$\sum_{n=1}^{N} \frac{CF_n}{(1+IRR)^n} - IIC = 0 \tag{9}$$

where IIC represents the initial investment cost; in this paper, it is the $C_{Investment}$ of each power station. N stands for the lifetime of the project. CF_n indicates the cash flows in year n (n = 1, 2, ..., N); for the construction period, it is equal to negative construction investment while in the operation period, it is equal to product sales profit (M_{Sale}) minus income tax. In particular, in the last year of the operation life, the residual value recovered by the power station should be added to this base.

By calculating the net profit and IRR under different scenarios, this paper analyzed the economic situation of energy storage power stations within the electricity market.

5. Case Analysis

5.1. Data

In this paper, a pumped storage power station (Yixing Pumped Storage Power Station) and a battery storage power station (Zhenjiang Electrochemical Power Station) were selected as examples to analyze the profits of energy storage in the electricity market. The geographical locations of the two power stations are shown in Figure 1. Pumped storage, as the most mature energy storage type with the largest installed capacity, has always received a great deal of attention. At the same time, the high-efficiency battery power station also has a broad application prospect for a reduced cost.

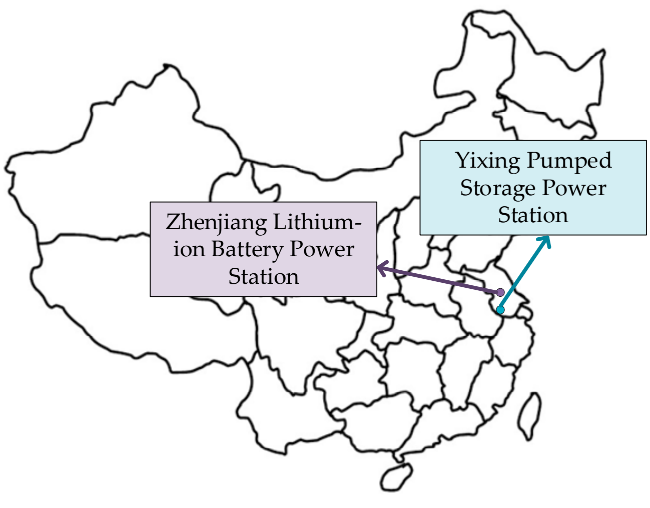

Figure 1. Geographical locations of the two selected power stations.

The specific data of these two energy storage power stations are shown in Table 1. As China's electricity market is still in its infancy and the market rules are incomplete, the energy storage station's revenue is calculated by referring to the rules and prices of the PJM market in the United States. The specific price data are given in Table 2.

Table 1. Data of the two selected storage power stations.

Relevant Information	Selected Power Station	
	Yixing Power Station	Zhenjiang Power Station
Energy Storage Type	Pumped storage	Lithium-ion battery
Total Installed Capacity (MW for pumped storage station, MW/MWh for battery storage station)	1000	101/202
Total Investment (USD)	676,831,694	85,261,183
Loan in Investment (USD)	641,408,515	0

Table 2. Summary of data required for calculations [32,33].

Capacity Market	
Basic auction market (USD/MW/day)	100
First additional auction market (USD/MW/day)	51.33
Second additional auction market (USD/MW/day)	32.87
Third additional auction market (USD/MW/day)	28.35
Energy Market	
Average peak price (USD/MW/h)	35.61
Average low price (USD/MW/h)	19.91
Charging time/discharging time (h)	12/12
Regulation Market	
Regulation price (USD/MW/h)	15
Regulation time (h)	24

For the capacity market, we used the clearing-price of the PJM capacity market for 2019 and 2020. For the energy market, the average peak/valley price of the PJM energy market in July 2019 was calculated and used. For the price of frequency regulation service, we use the average daily regulation price of the PJM frequency regulation market in July 2019.

In the case calculation, the payback period of the battery power station was 10 years, while that of the pumped storage power station was 40 years (due to its long life cycle). At the same time, for the battery power station, there is a 3% annual battery decay rate, that is, the capacity of the battery in the next year will be reduced to 97% of the previous year.

5.2. Results

5.2.1. Case Setup

(1) Base Case

First, this paper calculates the situation where the energy storage power station only participates in a certain market. Generally, the power station will not only participate in the capacity market, so here the energy market and frequency regulation market are respectively taken as the typical case of single-application scenarios.

At the same time, since China has not yet established the capacity market, we selected 30% of the station capacity to participate in the frequency regulation market, while the rest was devoted to participate in the energy market (i.e., 30% regulation market + 70% energy market) as the first typical example for multi-application scenarios. Nevertheless, in China's future electricity market, the capacity market will be an important component. Thus, on the basis of the first example for multi-application scenarios, we considered the benefits of energy storage power stations participating in the capacity market (i.e., 30% regulatory market + 70% energy market + 100% capacity market), and used this as the second typical example for multi-application scenarios. Next, by calculating the net profits and IRR of Yixing Pumped Storage Power Station and Zhenjiang Electrochemical Power Station in the above four case settings, the economic situation of energy storage power stations in the single-application scenario and multi-application scenarios were analyzed and compared.

(2) Profit Under Different Market Participation

The energy storage power station may participate in the electricity market in different forms. For example, it may decide whether or not to participate in the capacity market according to the power station planning and how to participate in the frequency regulation market and energy market due to the actual demand. Although China has not yet established the capacity market, considering the necessary position of the capacity market in the future electricity market, energy storage stations will participate in three markets at the same time in the following calculations. Here, we consider the energy storage power stations to participate in the energy and frequency regulation markets with different proportions, to analyze the sensitivity of different energy storage power stations to the market participation ratio.

(3) Influence of Subsidy Policy on Energy Storage

As an important strategic resource, various countries have issued relevant subsidy policies to support the development of energy storage. Since 2011, energy storage has been included in the support scope of SGIP (self-generation incremental program) in California [34]. In May 2018, the US Department of Energy announced that it would provide 30 million dollars for energy storage that can provide long-term support [35]. China has also issued a number of policies to support the development of energy storage. Among them, Suzhou Industrial Park subsidizes energy storage projects by 0.3 RMB/kWh (0.0426 USD/kWh) according to the power generation capacity, and it will be subsidized for three years after the project is put into operation [36].

This paper sets up three different subsidy policies (0.3 RMB/kWh, 0.5 RMB/kWh, and 1 RMB/kWh, i.e., 0.0426 USD/kWh, 0.071 USD/kWh, and 0.142 USD/kWh), calculates the economic benefits of energy storage power stations under different subsidy policies, and compares them with no subsidy. The subsidy period of the two power stations is ten years. Through these calculations, we can roughly calculate what kind of subsidy policy can sustain the development of energy storage power stations.

(4) Sensitivity Analysis of US Price

Since China's electricity market is still under construction and the market mechanism is not yet complete, the prices of each market referenced in this article are from the PJM market. However, the price of China's electricity market is uncertain and will not be exactly the same as the PJM market. Therefore, here, we carried out a sensitivity analysis on the economic benefits of different PJM price levels. In detail, we consider that China's electricity price can reach 80%, 90%, 100%, 110%, and 120% of the PJM price, and observe the impact of price changes on different power stations.

5.2.2. Results and Analysis

In the calculations of this paper, the operating life of Zhenjiang Electrochemical Power Station was 10 years, while that of Yixing Pumped Storage Power Station was 40 years. In order to compare on the same time scale, the following figures about net profit only shows the net profit of the two power stations in the previous ten years. At the same time, we choose 10% as the benchmark IRR, which means that the investment is valuable only when the IRR exceeds 10%.

(1) Base Case

The calculation results of the four base cases are shown in Figures 2–4. It can be seen from Figures 2 and 3 that energy storage power stations can obtain better benefits from participating in the frequency regulation market than participating in the energy market. At the same time, while countries begin to develop capacity markets, energy storage power stations can gain additional profits in the capacity market to make up for part of the economic losses. However, in general, when energy storage participates in the electricity market, the losses are serious according to the current market mechanism, especially when the station participates in the energy market alone (the annual loss of Yixing power station was about 35.52 million USD, and that of Zhenjiang power station was about 11.6 million USD).

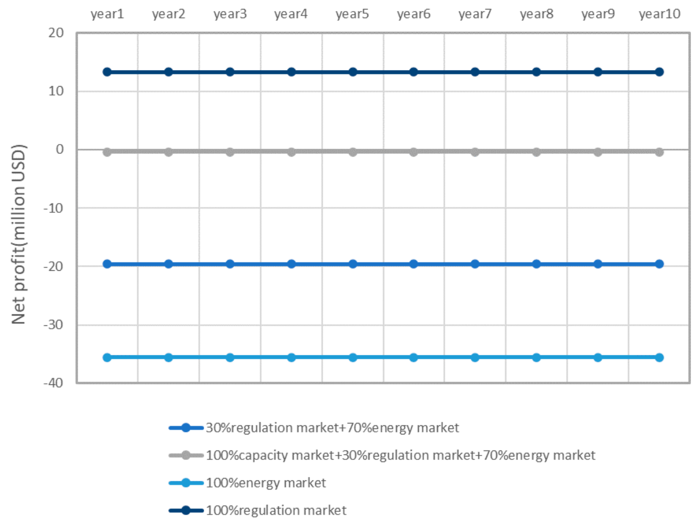

Figure 2. Net profit of Yixing power station participating in different applications.

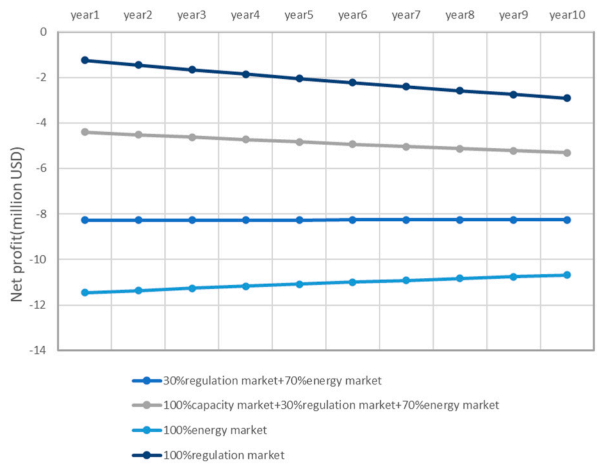

Figure 3. Net profit of Zhenjiang power station participating in different applications.

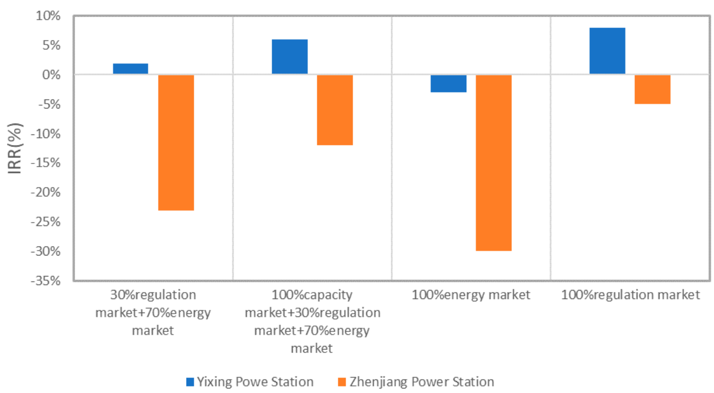

Figure 4. Internal rate of return (IRR) of power stations participating in different applications.

The IRR under the corresponding four cases is shown in Figure 4. Since Zhenjiang Electrochemical Power Station suffered too much loss when participating in the energy market alone, it was impossible to calculate IRR, so the IRR in this circumstance was set to the lowest value of 30%. As energy storage can obtain better returns in the frequency regulation market, the IRR will also become higher. At the same time, the IRR of the energy storage power station will also increase due to the revenue brought by the involvement of the capacity market. However, no matter how the energy storage power station participates in the electricity market, the IRR of both power stations does not exceed 10%. This means that there is always a risk of loss in the investment of energy storage power stations. Compared with that of electrochemical power stations, although the initial investment of pumped storage power stations is relatively large, the longer operating life lowers the cost of pumped storage stations that are evenly allocated to each year and obtains higher IRR.

(2) Profit Under Different Market Participation

The calculation results of the profit analysis under different market participations are shown in Figures 5–7.

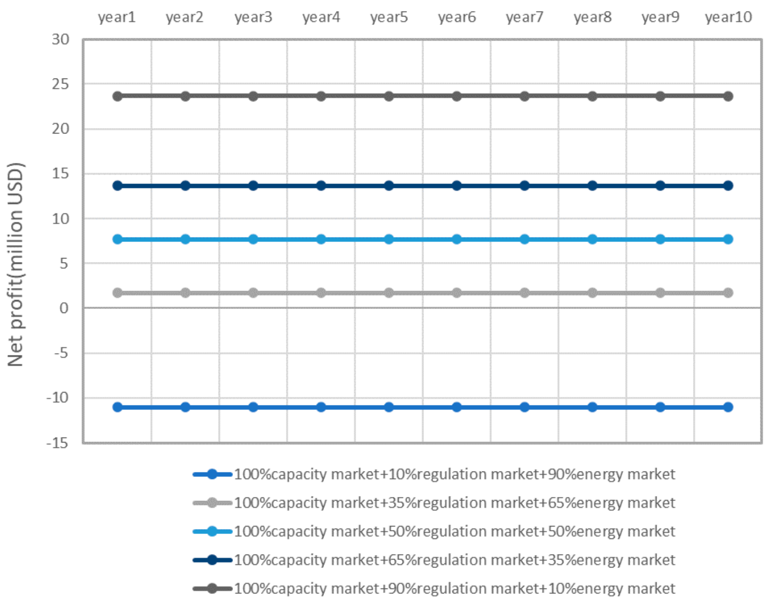

Figure 5. Net profit of Yixing power station under different market participations.

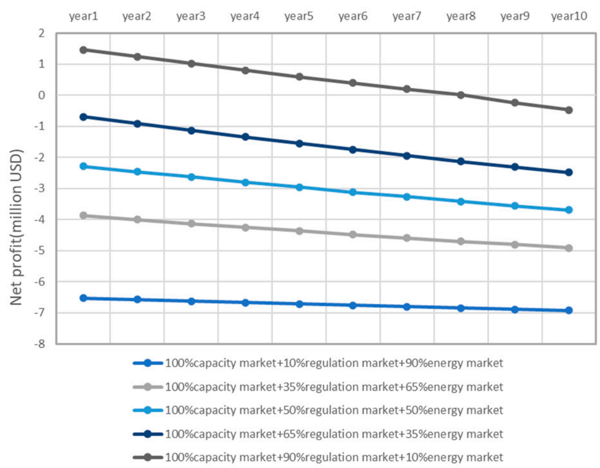

Figure 6. Net profit of Zhenjiang power station under different market participations.

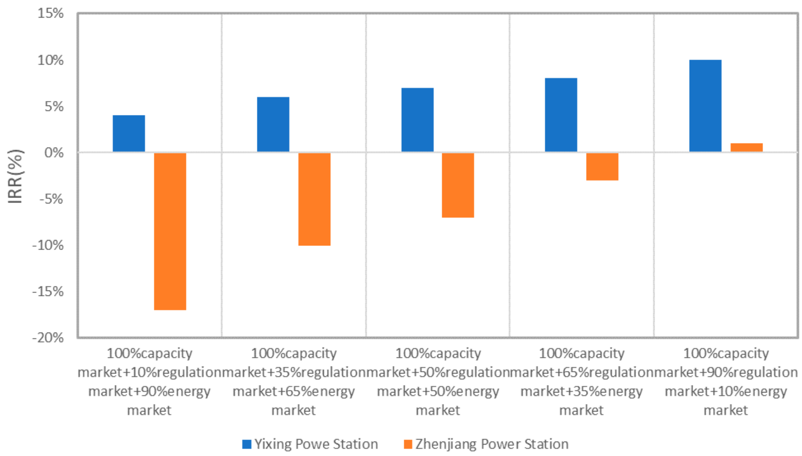

Figure 7. IRR under different market participations.

It can be seen from Figures 5 and 6 that with the decrease of energy market share and the corresponding increase of frequency regulation market share, the profits of energy storage power stations are also raised. That is to say, increasing the proportion of the frequency regulation market can help energy storage power stations obtain better benefits. At the same time, considering that energy storage can quickly respond to frequency changes and ensure the security of the power system, energy storage will play a more important role in the frequency regulation market.

Regarding the sensitivity of the two power stations to the market participation ratio, it can be seen in Figure 7 that with the increase of the frequency regulation market proportion, the IRR of both energy storage power stations becomes higher. However, due to the small capacity and initial investment of Zhenjiang electrochemical power station, the change of IRR is more obvious (increased from −17% to −1%), which means that Zhenjiang electrochemical power station is more susceptible to the influence of the market participation ratio.

(3) Influence of Subsidy Policy on Energy Storage

When the energy storage power station is fully involved in the capacity market and participating in the energy market and frequency regulation market with the proportions of 30% and 70%, the net profits and IRR of the two energy storage power stations under different subsidy policies were calculated, as shown in Figures 8–10.

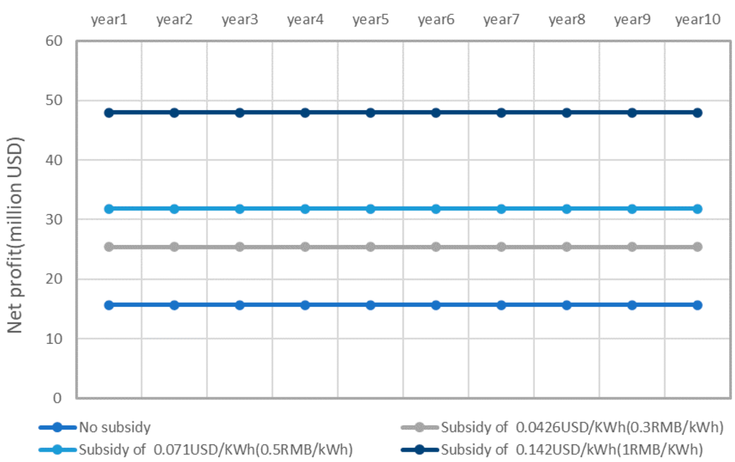

Figure 8. Net profit of Yixing power station with different subsidies.

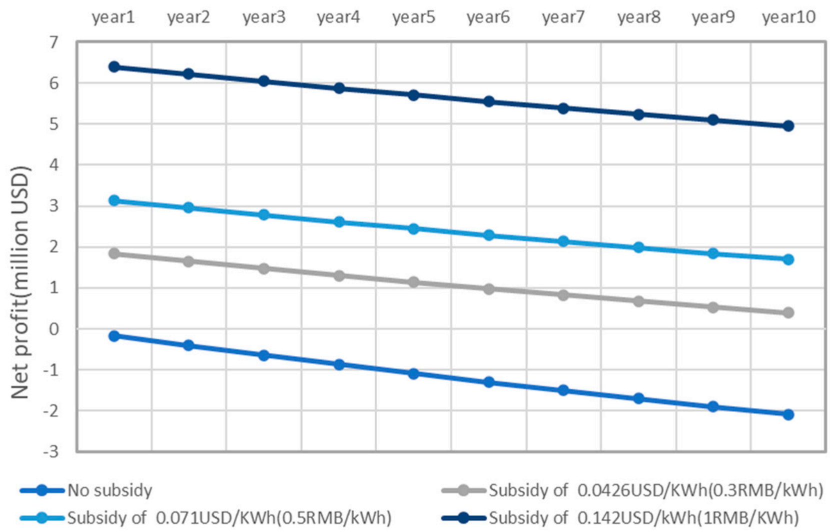

Figure 9. Net profit of Zhenjiang power station with different subsidies.

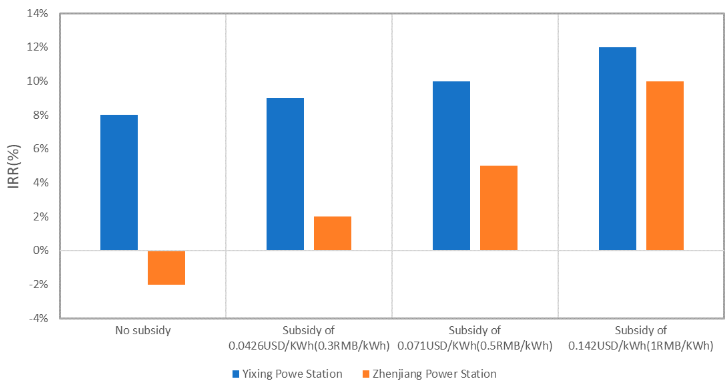

Figure 10. IRR of power station with different subsidies.

It can be seen from Figures 8 and 9 that appropriate subsidy policies can help energy storage power stations to recover their costs. Among them, Yixing Pumped Energy Power Station needs a subsidy of 0.071 USD/kWh (when the subsidy is 0.071 USD/kWh, the IRR of the Yixing Power Station can reach 10%), while the Zhenjiang Electrochemical Power Station needs a subsidy of 0.142 USD/kWh.

(4) Sensitivity Analysis of US Price

When participating in the market at different price levels, the results obtained vary greatly. Similarly, when the energy storage power station is fully involved in the capacity market and participating in the energy market and frequency regulation market with the proportions of 30% and 70%, the net profits and IRR of the two energy storage power stations under different price level were calculated.

As shown in Figures 11 and 12, when the price increases, energy storage revenue increases significantly. Regarding the sensitivity of the two power stations to different price levels, it can be seen in Figure 13 that the IRR change of the Zhenjiang Electrochemical Power Station is more obvious (increased from −8% to 2%), which means that Zhenjiang Electrochemical Power Station is more sensitive to the change of price. At the same time, when the price of China's electricity market reaches 110% of the PJM price, Yixing Power Station will meet the investment requirements under this specific market participation. However, although the IRR of Zhenjiang Electrochemical Power Station rises rapidly with the increase in price level, it still has a relatively large investment risk.

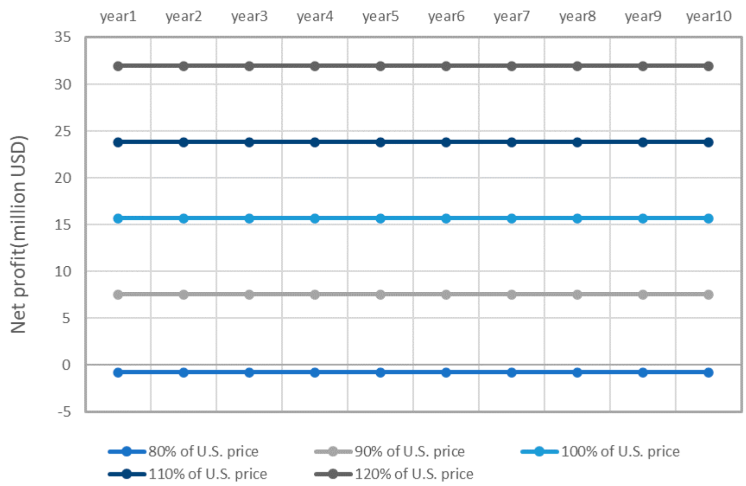

Figure 11. Net profit of Yixing power station with different price levels.

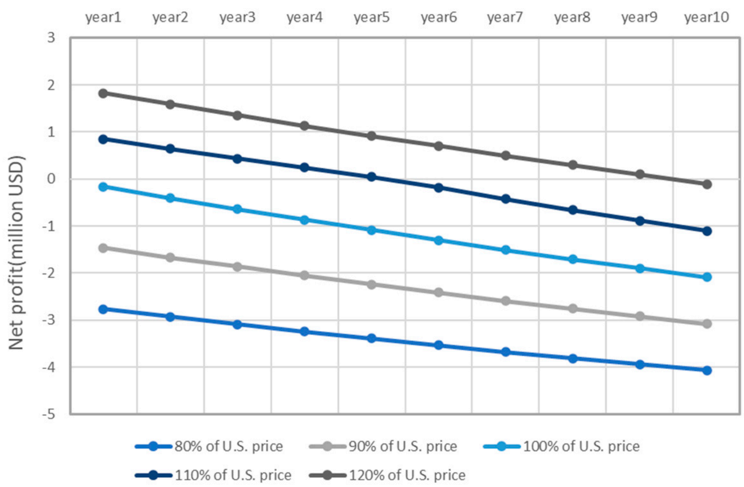

Figure 12. Net profit of Zhenjiang power station with different price levels.

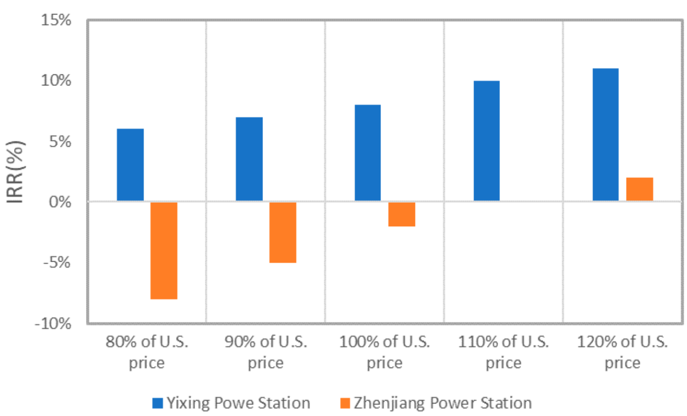

Figure 13. IRR of power station with different price levels.

6. Conclusions

In this paper, the cost–benefit model proposed under multi-application scenarios of energy storage was integrated into the income statement. Taking Yixing Pumped Storage Power Station and Zhenjiang Electrochemical Power Station as typical power stations, the economic conditions of energy storage in

China's future electricity market were analyzed by calculating their net profit and IRR. The results mainly show us the following four conclusions.

(1) Energy storage can gain more profits through additional participation in the capacity market, but without government subsidies, there are still great risks in energy storage investment. At the same time, pumped-storage power stations with more operating years have lower investment risks than electrochemical power stations due to their costs being evenly divided.
(2) Compared with the energy market, energy storage gets higher income from the frequency regulation market. With the increasing proportion of power stations participating in the frequency regulation market, the net profit and IRR of the two selected power stations correspondingly rise.
(3) Energy storage power stations can recover their costs with appropriate subsidies provided by the government. The subsidy of 0.071 USD/kWh can guarantee a valuable investment of pumped power stations, while that should be 0.142 USD/kWh for the electrochemical power station.
(4) Different market price levels have a great impact on energy storage economy. When the price of 110% of the PJM standard is reached, Yixing power station meets the investment IRR requirements, but Zhenjiang Power Station still faces greater challenges.

Different from the overall evaluation of the bulk grid-scale energy storage, where its revenue is lower than the value that it brings in most provinces in China [37], the results of this paper show that although electrochemical power stations still have great investment risks in China's future electricity market, pumped storage power stations can obtain higher profits with longer payback periods. Different policy supports can be given for different types of energy storage technologies.

Based on the work of this paper, there are still several areas that can be further studied.

(1) This paper adopts simplified market participation rules and an ideal model that does not take the risk caused by uncertain factors (such as natural disasters and policy changes) into account. In the further research, more practical market rules and more comprehensive models that combine risk cost and the potential value to externalities can be considered.
(2) The charging costs of each market are simply superimposed, which could be improved by more complicated calculations.

Author Contributions: Methodology, Z.W.; formal analysis, Y.W.; investigation, C.W.; original draft preparation, Z.W. and Y.W.; review and revise, Q.D. funding acquisition, K.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the "Fundamental Research Funds for the Central Universities", National Natural Science Foundation of China (No. 51977033 and No. 51907025), and the State Key Laboratory of Smart Grid Protection and Control (Analysis of Response Characteristics of Load Resources Control Technology of and Frequency Source-Grid-Load Coordination).

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

References

1. Sarkodie, S.A.; Strezov, V. Effect of foreign direct investments, economic development and energy consumption on greenhouse gas emissions in developing countries. *Sci. Total Environ.* **2019**, *646*, 862–871. [CrossRef] [PubMed]
2. Yu, S.W.; Hu, X.; Li, L.X.; Chen, H. Does the development of renewable energy promote carbon reduction? Evidence from Chinese provinces. *J. Environ. Manag.* **2020**, *268*, 110634. [CrossRef] [PubMed]
3. Abdmouleh, Z.; Alammari, R.A.M.; Gastli, A. Review of policies encouraging renewable energy integration & best practices. *Renew. Sustain. Energy Rev.* **2015**, *45*, 249–262.
4. Lin, B.Q.; Li, J.L. Analyzing cost of grid-connection of renewable energy development in China. *Renew. Sustain. Energy Rev.* **2015**, *50*, 1373–1382. [CrossRef]
5. Yuan, W.; Wang, C.X.; Lei, X.J.; Li, Q.H.; Shi, Z.Y.; Yu, Y. Multi-area scheduling model and strategy for power systems with large-scale new energy and energy storage. In Proceedings of the 2018 Chinese Automation Congress (CAC), Xi'an, China, 30 November–2 December 2018; pp. 2419–2424.

6. Zhang, N.; Lu, X.; McElroy, M.B.; Nielsen, C.P.; Chen, X.Y.; Deng, Y.; Kang, C.Q. Reducing curtailment of wind electricity in China by employing electric boilers for heat and pumped hydro for energy storage. *Appl. Energy* **2016**, *184*, 987–994. [CrossRef]
7. Zhang, N.; Kang, C.Q.; Kirschen, D.S.; Xia, Q.; Xi, W.M.; Huang, J.H.; Zhang, Q. Planning pumped storage capacity for wind power integration. *IEEE Trans. Sustain. Energy* **2013**, *4*, 393–401. [CrossRef]
8. Ummels, B.C.; Pelgrum, E.; Kling, W.L. Integration of large-scale wind power and use of energy storage in the Netherlands' electricity supply. *IET Renew. Power Gener.* **2008**, *2*, 34–46. [CrossRef]
9. Chen, C.Y.; Cui, M.J.; Li, F.X.; Yin, S.F.; Wang, X.A. Model-Free Emergency Frequency Control Based on Reinforcement Learning. *IEEE Trans. Ind. Inform.* **2020**. [CrossRef]
10. Shim, J.W.; Verbic, G.; Kim, H.; Hur, K. On droop control of energy-constrained battery energy storage systems for grid frequency regulation. *IEEE Access* **2019**, *7*, 166353–166364. [CrossRef]
11. Tan, J.; Zhang, Y.C. Coordinated Control Strategy of a Battery Energy Storage System to Support a Wind Power Plant Providing Multi-Timescale Frequency Ancillary Services. *IEEE Trans. Sustain. Energy* **2017**, *8*, 1140–1153. [CrossRef]
12. Mercier, P.; Cherkaoui, R.; Oudalov, A. Optimizing a battery energy storage system for frequency control application in an isolated power system. *IEEE Trans. Power Syst.* **2009**, *24*, 1469–1477. [CrossRef]
13. Koohi-Fayegh, S.; Rosen, M.A. A review of energy storage types, applications and recent developments. *J. Energy Storage* **2020**, *27*, 101047. [CrossRef]
14. Zhou, B.R.; Liu, S.H.; Lu, S.Y.; Cao, X.Y.; Zhao, W.M. Cost–benefit analysis of pumped hydro storage using improved probabilistic production simulation method. *J. Eng.* **2017**, *13*, 2146–2151. [CrossRef]
15. Guo, Z.; Ge, S.S.; Yao, X.L.; Li, H.; Li, X.Y. Life cycle sustainability assessment of pumped hydro energy storage. *Int. J. Energy Res.* **2020**, *44*, 192–204. [CrossRef]
16. Li, X.; Chalvatzis, K.J.; Stephanides, P. Innovative Energy Islands: Life-Cycle Cost-Benefit Analysis for Battery Energy Storage. *Sustanability* **2018**, *10*, 3371. [CrossRef]
17. Mateo, C.; Reneses, J.; Rodriguez-Calvo, A.; Frias, P.; Sanchez, A. Cost-benefit analysis of battery storage in medium-voltage distribution networks. *IET Gener. Transm. Distrib.* **2016**, *10*, 815–821. [CrossRef]
18. Lin, B.; Wu, W. Economic viability of battery energy storage and grid strategy: A special case of China electricity market. *Energy* **2017**, *124*, 423–434. [CrossRef]
19. Krishnan, V.; Das, T. Optimal allocation of energy storage in a co-optimized electricity market: Benefits assessment and deriving indicators for economic storage ventures. *Energy* **2015**, *81*, 175–188. [CrossRef]
20. Das, T.; Krishnan, V.; McCalley, J.D. Assessing the benefits and economics of bulk energy storage technologies in the power grid. *Appl. Energy* **2015**, *139*, 104–118. [CrossRef]
21. Rupp, A.; Baier, H.; Mertiny, P.; Secanell, M. Analysis of a flywheel energy storage system for light rail transit. *Energy* **2016**, *107*, 625–638. [CrossRef]
22. Mehrjerdi, H.; Rakhshani, E. Optimal operation of hybrid electrical and thermal energy storage systems under uncertain loading condition. *Appl. Therm. Eng.* **2019**, *160*, 114094. [CrossRef]
23. Zafirakis, D.; Chalvatzis, K.J.; Baiocchi, G.; Daskalakis, G. The value of arbitrage for energy storage: Evidence from European electricity markets. *Appl. Energy* **2016**, *184*, 971–986. [CrossRef]
24. Yao, L.Z.; Yang, B.; Cui, H.F.; Zhuang, J.; Ye, J.L.; Xue, J.H. Challenges and progresses of energy storage technology and its application in power systems. *J. Mod. Power Syst. Clean Energy* **2016**, *4*, 519–528. [CrossRef]
25. Aneke, M.; Wang, M.H. Energy storage technologies and real life applications—A state of the art review. *Appl. Energy* **2016**, *179*, 350–377. [CrossRef]
26. Vazquez, S.; Lukic, S.M.; Galvan, E.; Franquelo, L.G.; Carrasco, J.M. Energy storage systems for transport and grid applications. *IEEE Trans. Ind. Electron.* **2010**, *57*, 3881–3895. [CrossRef]
27. Zakeri, B.; Syri, S. Electrical energy storage systems: A comparative life cycle cost analysis. *Renew. Sustain. Energy Rev.* **2015**, *42*, 569–596. [CrossRef]
28. Zeng, M.; Feng, J.J.; Xue, S.; Wang, Z.J.; Zhu, X.L.; Wang, Y.J. Development of China's pumped storage plant and related policy analysis. *Energy Policy* **2013**, *61*, 104–113.
29. IRENA. Electricity Storage and Renewables: Costs and Markets to 2030. 2017. Available online: https://www.irena.org/publications/2017/Oct/Electricity-storage-and-renewables-costs-and-markets (accessed on 13 July 2020).

30. Micro Energy Network Industry Alliance. Analysis of Energy Storage Cost Per Kilowatt Hour and Mileage Cost. 2019. Available online: https://www.sohu.com/a/343141699_99895902 (accessed on 13 July 2020). (In Chinese)
31. Shafiee, M.; Alghamdi, A.; Sansom, C.; Hart, P.; Encinas-Oropesa, A. A Through-Life Cost Analysis Model to Support Investment Decision-Making in Concentrated Solar Power Projectss. *Energies* **2020**, *13*, 7. [CrossRef]
32. PJM. Data Miner 2. 2017. Available online: https://dataminer2.pjm.com/feed/reg_prices/definition (accessed on 21 August 2019).
33. PJM. Capacity Market (RPM). 2019. Available online: https://www.pjm.com/markets-and-operations/rpm.aspx (accessed on 21 August 2019).
34. Zhongguancun Energy Storage Industry Technology Alliance. 2018. Available online: http://chuneng.bjx.com.cn/news/20180821/922398.shtml (accessed on 13 July 2020). (In Chinese)
35. China Energy Storage Network News Center. How Much Does DOE Spend to Promote Energy Storage Technology and Application? 2020. Available online: http://www.escn.com.cn/news/show-815212.html (accessed on 13 July 2020). (In Chinese)
36. Suzhou Industrial Park Management Committee. 2019. Available online: http://www.china-epc.org/zixun/2019-03-28/35006.html (accessed on 13 July 2020). (In Chinese)
37. Ding, J.; Xu, Y.; Wang, Z.; Hu, S.; Chen, H. Estimating the Economics of Electrical Energy Storage Based on Different Policies in China. *J. Therm. Sci.* **2020**, *29*, 352–364. [CrossRef]

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).