energies

Article

Subsidy Policies and Economic Analysis of Photovoltaic Energy Storage Integration in China

Wenhui Zhao [1], Rong Li [1,*] and Shuan Zhu [2]

1 College of Economics and Management, Shanghai University of Electric Power, Shanghai 200090, China; zhao_wenhui@shiep.edu.cn
2 Shanghai Qiyuan Green Power Technology Co., Ltd., The Green Energy Transportation Industry Innovation Center of SPIC, Shanghai 200090, China; shuanzhu@cpirhzl.com
* Correspondence: lirong@mail.shiep.edu.cn

Abstract: In the context of China's new power system, various regions have implemented policies mandating the integration of new energy sources with energy storage, while also introducing subsidies to alleviate project cost pressures. Currently, there is a lack of subsidy analysis for photovoltaic energy storage integration projects. In order to systematically assess the economic viability of photovoltaic energy storage integration projects after considering energy storage subsidies, this paper reviews relevant policies in the Chinese photovoltaic energy storage market. It analyzes the cost and revenue composition of photovoltaic energy storage integration projects, and constructs a system dynamics model for the levelized cost of electricity (LCOE) of such projects. Taking a specific photovoltaic energy storage project as an example, this paper measures the levelized cost of electricity and the investment return rate under different energy storage scenarios. Combining energy storage allocation ratios and internal rate of return indicators, this paper analyzes the net present value of photovoltaic energy storage integration projects under different subsidy standards. The results indicate that, while the current energy storage subsidy policies positively stimulate photovoltaic energy storage integration projects, they exhibit a limited capacity to cover energy storage investment costs, thereby failing to incentivize capital market participation in the construction of such projects. Rational allocation of energy storage capacity and optimization of corresponding subsidy policies are crucial prerequisites for enhancing the economic viability and widespread adoption of photovoltaic energy storage integration projects. This study not only aids in investment decision making for photovoltaic power stations but also contributes to the formulation of energy storage subsidy policies.

Keywords: photovoltaic energy storage integration; LCOE; net present value; energy storage subsidy; system dynamics

check for updates

Citation: Zhao, W.; Li, R.; Zhu, S. Subsidy Policies and Economic Analysis of Photovoltaic Energy Storage Integration in China. *Energies* **2024**, *17*, 2372. https://doi.org/10.3390/en17102372

Academic Editor: Gerardo Maria Mauro

Received: 6 March 2024
Revised: 26 April 2024
Accepted: 10 May 2024
Published: 14 May 2024

1. Introduction

1.1. Background

In December 2023, at the twenty-eighth Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) (referred to as "COP28"), the "Global inventory text" was released, which attracted worldwide attention, calling on countries to triple the installed capacity of global renewable energy by 2030 to scientifically achieve the goal of net zero emissions by 2050 [1]. With the acceleration of the process of "carbon neutrality", the trend of developing clean and low-carbon energy represented by photovoltaic on a global scale remains unchanged. At present, photovoltaic power generation has fully entered the stage of large-scale development, and the global new photovoltaic installed capacity continues to increase. According to the International Energy Agency (IEA) data, the cumulative installed capacity of global photovoltaic power exceeded 1100 GW in 2022, and the new installed capacity of global photovoltaic power generation increased from 30.2 GW in 2011 to 197 GW in 2022, of which there is 87.41 GW of new

PV installed capacity in China. Driven by China's long-term policy guidance and market support [2], photovoltaic will become the main force in building a new power system, and China has proposed that the total installed capacity of wind power and solar power will reach more than 1.2 billion kilowatts by 2030. After years of rapid development, China's photovoltaic industry ranks among the top in the world in terms of technology level and manufacturing scale [3].

In recent years, the continuous reduction in the cost of photovoltaic components and policy-driven initiatives have rapidly improved the economic viability of photovoltaic (PV) power plant operations [4]. The International Renewable Energy Agency (IRENA) released the "2021 Renewable Energy Electricity Cost Report", which revealed that from 2010 to 2022, the global solar PV cost experienced the fastest decline in cost, with the average levelized cost of electricity (LCOE) decreasing from 0.445 US dollars per kilowatt-hour (kWh) to 0.049 US dollars per kWh, a reduction of 89%. However, with the rapid increase in the penetration rate of PV power generation in China, the power system is facing a shortage of flexibility resources, and the issue of curtailed power due to the variability of PV power generation is becoming increasingly prominent [5]. To enhance the flexibility of PV power plants and reduce curtailed power, Chinese provinces and cities have introduced the "Compulsory Storage" policy, which mandates the integration of energy storage as a precondition for connecting new energy sources to the grid or obtaining approval. For example, in 2021, Jiangxi Province, China, issued a notice regarding the selection of competitive and preferred projects for new PV power generation in 2021, which stated that "in 2021, new PV power generation projects selected for competitive optimization in the province can voluntarily choose the integrated construction model of solar and storage, with the energy storage capacity not less than 10% of the installed capacity of the PV power station per hour, and the energy storage power station is generally built no later than the synchronous completion of the PV power station". Driven by policy, photovoltaic energy storage (PV-ES) integration projects have begun to enter the market as an efficient solution. PV-ES integration refers to the addition of energy storage inverters, energy storage batteries, and other energy storage system equipment in the PV power generation system, effectively addressing the shortcomings of intermittent, fluctuating, and low controllable PV power generation, resolving the contradiction between continuous power generation and intermittent power consumption, and achieving stable operation of electricity on the generation side, grid side, and user side. However, the current challenge faced by PV projects with storage is the high cost, which makes the economic viability difficult to demonstrate and significantly increases project investment risks. Without a rapid reduction in costs or the endorsement of new support policies, it is challenging to stimulate investor enthusiasm and to truly realize the profit mode of solar-storage integration projects. Although solar-storage integration projects are facing the high-cost pressure of storage, China's many regions have simultaneously introduced corresponding energy storage subsidy policies while promoting the compulsory allocation of new energy sources. For example, in December 2022, the People's Government of Inner Mongolia Autonomous Region issued a document stating that energy storage power stations included in the region's demonstration projects will enjoy capacity subsidies, with a subsidy of 0.35 yuan per kilowatt-hour for actual discharges, and the subsidy period will not exceed ten years".

The valuation of PV-ES integration projects places greater emphasis on economic viability, wherein the contribution of energy storage is a crucial component of the project's revenue, aiming to prevent distortions in the original intention of PV-ES integration due to profitability challenges associated with storage configuration. Therefore, assessing whether PV-ES integration projects can achieve expected returns under the consideration of energy storage subsidies is pivotal in evaluating project feasibility. Due to the incorporation of energy storage, both the cost and revenue composition of PV-ES integration projects undergo changes, with factors involved in the system dynamically evolving and mutually influencing throughout the entire lifecycle. This renders it difficult to accurately assess the cost and revenue levels of PV-ES integration projects. Hence, it is of practical significance to comprehensively consider the cost and revenue composition of PV-ES integration projects throughout their entire lifecycle and construct a dynamic measurement model for the LCOE-NPV of such projects, facilitating informed decision making and the formulation of corresponding energy storage policies.

1.2. Literature Review

The integration of energy storage with photovoltaic (PV) systems forms a PV-energy storage system, enabling the bidirectional flow of electric current. This system concurrently possesses the functionality of energy storage batteries and a highly reliable power supply source [6]. It can enhance the reliability and quality of the power system, as well as improve the grid's capacity to accommodate renewable energy sources [7]. Presently, research in China on PV-energy storage systems predominantly focuses on energy management and control strategies [8–10], system design [11,12], and development forecasting [13], with relatively limited attention to economic studies. In recent years, as PV has rapidly developed and energy storage has been extensively promoted, the economic issues related to PV-configured energy storage projects have garnered significant attention. Both domestic and international research efforts have predominantly concentrated on the analysis of costs associated with PV and energy storage systems, as well as the investment benefits of PV-energy storage system integration.

The investment costs of photovoltaic (PV) and energy storage systems significantly influence the economic viability of projects. A comprehensive life-cycle cost assessment model is established for user PV system generation projects in [14]. Through an analysis of various user types in Spain, it was discovered that the initial investment cost of PV generation systems is the primary factor affecting overall PV station costs. Aimed at minimizing life-cycle costs, an optimization model is constructed using a hybrid particle swarm and generalized pattern search algorithm in [15]. A minimal generation premium model is proposed to effectively schedule intermittently available, low-cost solar energy in [16]. A case study conducted in Minnesota demonstrated that reducing investment costs and, when necessary and appropriate, decreasing PV generation can minimize unit premiums. Literature [17] addressed three large-scale energy storage applications: pumped hydro storage, compressed air energy storage, and lithium iron phosphate battery storage. By integrating a life-cycle analysis of energy storage systems and calculating their total life-cycle costs, this study provided an objective and unified standard for cost assessments of various energy storage schemes, ensuring optimal economic benefits throughout the entire life cycle of energy storage systems.

As photovoltaic (PV) technology matures, the evaluation of its economic feasibility, particularly when compared to other power generation technologies, often employs the Levelized Cost of Electricity (LCOE). The LCOE model and the economic evaluation index were used to analyze distributed PV systems and found that the maturity of PV technology and the decline in investment costs have contributed to the fact that distributed PV can quickly achieve the goal of parity [18]. The literature [19], by summarizing and synthesizing policies and influencing factors related to distributed PV projects, coupled with the LCOE model and Net Present Value, conducted an economic study on distributed PV. Based on the LCOE model, the literature [20] calculated the costs of PV electricity generation, simulating the impacts of reductions in total plant costs, construction investment costs on PV electricity costs. The findings highlighted the significant influence of construction investment on costs within the LCOE model.

The Levelized Cost of Electricity is constructed considering factors such as PV system costs, operational costs, and tax costs in [21]. By employing the LCOE model to forecast centralized and distributed PV costs in 2025, the study revealed that the prioritization of centralized and distributed PV costs differs when considering transmission costs. The technical and economic impacts of energy storage system design on the feasibility of PV power plants are explored in [22]. The study found that although the molten chloride double-tank energy storage system has the lowest storage cost, integration with PV leads to a higher LCOE compared to other research designs. The Levelized Cost of Storage (LCOS) is predicted for different energy storage technologies from 2015 to 2050 based on trends in investment cost reductions and current performance parameters [23]. The research indicated that by 2030 and 2050, the LCOS of various storage technologies in simulated applications would decrease by one-third to one-half. Starting from 2030, lithium-ion may become the most cost-effective energy storage technology in almost all fixed applications.

In the aspect of investment and profitability analysis of photovoltaic energy storage systems, literature [24] constructs a cost-benefit model based on the structure of distributed photovoltaic energy storage systems to evaluate and compare the net income and cost-profit ratio of different user types under different electricity price models. The research indicates that the costs of photovoltaic and storage, load characteristics, and user electricity price models significantly influence the economic viability of the system. The cost-benefit model are established for distributed photovoltaics with and without storage systems under different operating modes in [25]. Through case analysis of different users, the study suggests that the economic feasibility of installing storage systems is lower for residential users, while the economic advantage of installing storage systems is relatively significant for business users. Literature [26] focuses on distributed photovoltaic energy storage systems and establishes cost-benefit models for investment economics, carbon emissions over the lifecycle, and energy analysis. By evaluating the economic, carbon emission, and energy benefits of a distributed photovoltaic and energy storage project in Jiaozhou, Shandong, China, it is concluded that adding storage systems to photovoltaic systems reduces investment profitability. The cost-minimization economic model is established for distributed photovoltaic and storage systems with and without energy storage management methods based on the structural characteristics of grid-connected distributed photovoltaic storage systems in [27]. By comparing the economic efficiency of the two modes, the study suggests that configuring storage systems can not only improve the utilization of photovoltaic power generation but also enhance grid stability.

With the development of renewable energy sources, subsidy policies have helped to improve the financial situation of power producers, and many articles have identified incentive policies as an important factor influencing the effectiveness of renewable energy investments. The experience of the last three decades of solar and wind energy development in Europe shows that end-product subsidy schemes play an important role in the transition to renewable energy. An exemplary subsidization path to empower large-scale growth in a market for green hydrogen is defined in [28], and the subsidization schemes from other renewable markets are provided. A method for policymakers to more accurately study the financial performance of residential solar photovoltaics from the perspective of consumers is proposed in [29]. Taking Ireland as a case study, a series of prospective policy scenarios are modeled, comparing policy mechanisms such as compensating homeowners for electricity generation, reducing upfront costs, and assisting with financing. The research indicates that more generous financial incentive programs can accelerate the investment payback period. A mathematical model for the performance of distributed photovoltaic energy storage systems is established in [30]. By comparing the investment payback periods of distributed photovoltaic energy storage systems with and without incentive policies, the effectiveness of incentive policies for different locations and building types is evaluated. The research shows that current incentive policies can shorten the investment payback period of projects. China is not mature enough to develop incentives for renewable energy development, so a study of incentives for photovoltaic storage energy development in China is necessary [31].

In summary, there is already a certain research foundation on the economic feasibility of photovoltaic combined with storage systems both domestically and internationally. However, studies regarding system costs mostly analyze investment costs of photovoltaic systems and storage systems, with less emphasis on the generation costs of photovoltaic storage systems. Moreover, the cost–benefit estimation methods commonly used in existing research are mostly static, which may result in lower accuracy of LCOE (levelized cost of electricity) models due to the dynamic and interrelated nature of variables such as storage equipment replacement costs and revenues over the lifecycle of PV-ES integration projects. Furthermore, while the Chinese government has introduced new energy storage policies and corresponding subsidies to promote renewable energy consumption, few scholars have considered the economic effects of energy storage subsidies on "new energy + storage" projects. Given the current substantial efforts in China to promote energy storage, neglecting this aspect in LCOE calculations for PV-ES integration projects may lead to significant deviations in the analysis results. It is hoped that this study can fill this gap and provide more detailed information for the policy system of China's photovoltaic storage market.

Therefore, this research thoroughly analyzes the composition elements and causal relationships of costs and benefits throughout the lifecycle of PV-ES integration projects, constructs a dynamic LOCE-NPV (levelized cost of energy-net present value) system model, and takes a specific photovoltaic storage project as an example to simulate the development trend of PV-ES integration projects under different storage configuration ratios and subsidy mechanisms. It also analyzes the effectiveness of relevant energy storage subsidy policies to provide reference for optimizing energy storage subsidy policies and further promoting the development and application of PV-ES integration projects in China. The work of this paper provides a dynamic solution for evaluating the economic feasibility of PV-ES integration projects, which can be applied to compare different configurations of photovoltaic and storage systems and help determine their competitiveness with other competing options. This research helps policymakers better understand the impact of energy storage subsidies on investment decisions for PV-ES integration projects, thereby designing and optimizing corresponding policies more accurately to achieve greater social benefits. It also aims to provide valuable references for enterprises investing in and operating photovoltaic storage power stations, enabling them to analyze the economic feasibility of PV-ES integration projects by considering government subsidy factors and make more rational decisions to promote the development and application of PV-ES integration projects more effectively. These points represent the major contributions of this paper.

2. The Development Status of China's Photovoltaic Energy Storage Market

2.1. General Situation

According to the incomplete statistics from the Global States Exchange Technology (CNESA) Global Energy Storage Project Database, as of the end of 2020, China has cumulatively installed a capacity of 883.0 MW in photovoltaic (PV) energy storage projects, accounting for approximately 27.0% of the total installed capacity of electrochemical energy storage projects in China. The annual growth rate is reported to be 132.3%. In 2020, the newly commissioned electrochemical energy storage projects in China reached a cumulative installed capacity of 1559.6 MW, surpassing the gigawatt threshold for the first time, with a year-on-year growth of 145%. Notably, energy storage on the power generation side contributed to nearly half of the installed capacity, especially with the completion and operation of several large-scale photovoltaic energy storage projects, leading to a record-high increase in the newly commissioned capacity of such projects in 2020. Against the backdrop of the "Dual Carbon" strategy, China is actively promoting the construction of "PV-ES Integration" projects. As shown in Figure 1, the global cumulative installed capacity of PV energy storage reached approximately 11.5 GW in 2021, representing a 56.65% year-on-year growth. China's installed capacity accounted for 30.43% of the total installed capacity, reaching approximately 3.5 GW, with a growth rate exceeding three times compared to the same period last year. Most of the already commissioned PV-ES integration projects are located in western provinces of China, as indicated in Table 1.

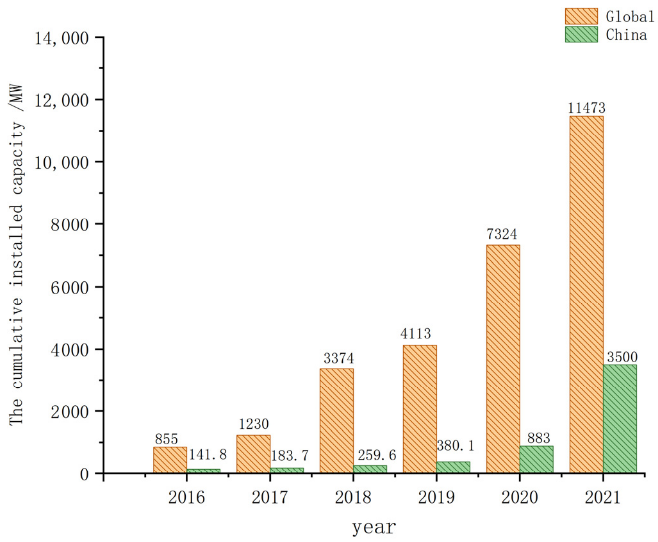

Figure 1. Global and China's cumulative installed capacity of photovoltaic energy storage.

Table 1. Typical PV-ES integrated project put into operation in China.

Project Name	Project Location	Installed Capacity of Photovoltaic Power Generation/MW	Energy Storage Capacity/MWh
Kezuohou Banner 100 MW Photovoltaic Energy Storage Project	Kezuohou Banner, Tongliao City, Inner Mongolia	100	30 MW/60 MWh
360 MW + 60 MW/120 MWh Photovoltaic Energy Storage Fusion Power StationProject	Laizhou City, Shandong Province	360	60 MW/120 MWh
Shengtong Industrial Park Photovoltaic Storage Integration Project	Changsha, Hunan Province	9.8	16.5 MW/40 MWh
Three Gorges 10 MW Centralized Photovoltaic Storage Project	Badu County, Qamdo City, Tibet Autonomous Region	10	2.5 MW/10 MWh
Hangzhou Bay Geely Automobile (polar Krypton factory) Distributed Photovoltaic Storage Project	Ningbo City, Zhejiang Province	29	6 MW/12 MWh
Low Carbon Campus Vanadium Flow Battery PV Storage And Charging Integrated Project	Shuozhou city, Shanxi Province	1.705	25 kW/100 kWh

Examining the application distribution of commissioned PV energy storage projects in China, it is observed that in projects involving centralized renewable energy configuration and energy storage, the installed capacity proportion of PV energy storage projects is 79.4%. By the end of 2020, the cumulative installed capacity of projects associated with centralized photovoltaic power stations reached 669.0 MW, constituting 75.8% of the total installed capacity of all PV energy storage projects. These projects are mainly distributed in Qinghai, Shandong, Tibet, Xinjiang, and other regions. Notably, Qinghai maintained its leading position with a cumulative installed capacity of 290.3 MW, accounting for 43.4% of the total. In projects related to distributed renewable energy configuration and energy storage, the installed capacity proportion of PV energy storage projects is 11.9%. By the end of 2020, the cumulative installed capacity of projects combining distributed photovoltaics amounted to 214.0 MW, representing 24.2% of all PV energy storage projects.

2.2. Relevant Policy

2.2.1. Policies Related to the Configuration of Energy Storage for Photovoltaic Projects

In recent years, China has placed significant emphasis on the coordinated development of new energy and energy storage, enacting a series of policy measures to promote the development of "new energy + energy storage". From 2021 to present, a total of 26 provinces have introduced policies regarding the integration of new energy with energy storage. Among these, many local policies include provisions for photovoltaic (PV) energy storage integration. Overall, the requirements for the scale of PV power station storage integration across various regions range from 5% to 30% of the installed capacity, with storage duration primarily ranging from 2 to 4 h, while a few regions require a storage duration of 1 h. Specifically, in the policies issued by various regions, the highest requirements for the scale and duration of PV storage integration are found in Zaozhuang, Shandong Province, which stipulates a storage integration scale of 15% to 30% of the installed capacity (subject to timely adjustment based on different development stages) and a duration of 2 to 4 h for the storage facilities. Additionally, Shanghai, Gansu, and other regions require a storage integration ratio of 20%. Some of the domestic policies related to PV storage integration are illustrated in Figure 2.

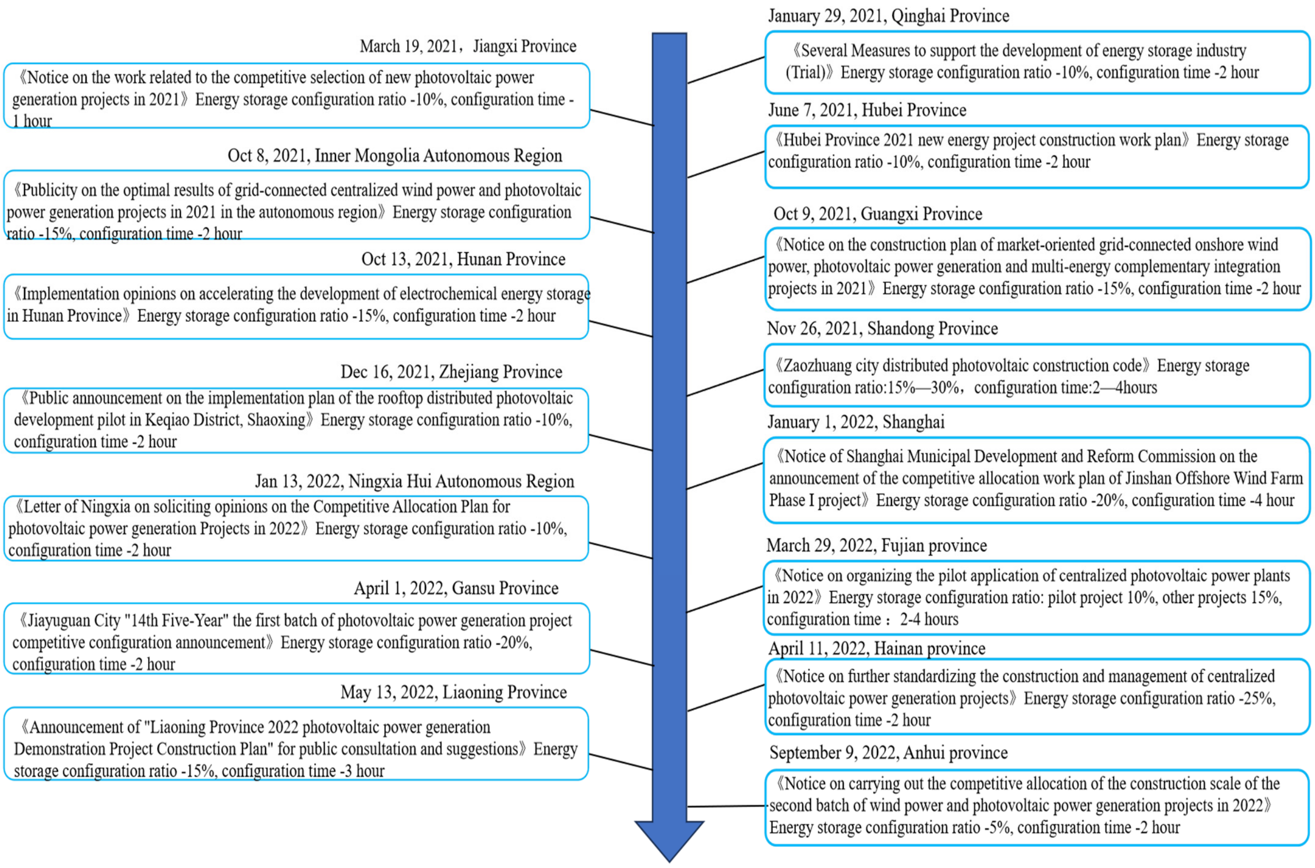

Figure 2. China's partial photovoltaic project allocation and storage related policies.

2.2.2. Policies Related to Energy Storage Subsidies

In recent years, the state has introduced a series of policies to explicitly promote the development of energy storage, continuously enhancing the favorable policies for energy storage. Regions across the country have actively implemented subsidies for energy storage to facilitate its development. As of 2022, 28 regions including Leqing in Zhejiang Province, Nanjing in Jiangsu Province, Shunde in Foshan, Shaanxi, Shenyang in Liaoning Province, Guangzhou, Tianjin, Qinghai, Xi'an in Shaanxi Province, Yiwu in Zhejiang Province, and Hefei in Anhui Province have issued policies regarding subsidies for energy storage. Currently, the main beneficiaries of energy storage subsidies are standalone energy storage projects and projects combining new energy with energy storage. Overall, the current subsidy methods for energy storage mainly include initial investment subsidies for energy storage projects and discharge volume subsidies. These subsidy forms are generally reflected in all regions where energy storage subsidy policies have been implemented. Additionally, a small number of policies provide subsidies for energy storage charging volume, as well as response subsidies for installing energy storage to participate in demand response services. Specifically, the current subsidy settings for energy storage, whether for discharge volume or initial investment, mostly have subsidy caps. Energy storage subsidies serve as beneficial supplements; however, the successful implementation of actual projects depends not only on subsidies but also on local electricity market policies, among other factors. For detailed information on some domestic energy storage subsidy-related policies in 2022, refer to Table 2.

Table 2. Part of the policy related to domestic energy storage subsidies in 2022.

Region	Subsidy Amount	Main Content
Yueqing City, Zhejiang Province	0.89 yuan/kWh	The subsidy of 0.89 yuan/kWh on the basis of the existing electricity price 0.89 yuan/kWh
Nanjing City, Jiangsu Province	0.2 yuan/kWh	The subsidy of 0.2 yuan/kWh for the operation of photovoltaic energy storage charging and discharging facilities above 500 kWh
Foshan City, Guangdong Province	10~30 (104¥)	The one-time subsidy for the purchase of energy storage equipment in many places in Shunde ranges from 100 thousand yuan to 300 thousand yuan
Shenyang City, Liaoning Province	10% of the investment	Photovoltaic energy storage charging demonstration stations are rewarded by 10% of the investment, with a maximum of 500 thousand yuan per station
Qinghai Province	0.1 yuan/kWh	The subsidy for new energy distribution and storage projects is 0.1 yuan/kWh
Xi'an City, Shanxi Province	No more than half a million	From 1 January 2021 to 31 December 2023, energy storage systems of not less than 1 MWh will be subsidized by investment enterprises based on 20% of the actual investment in energy storage equipment, with a maximum of 500 thousand yuan
Yiwu City, Zhejiang Province	0.25 yuan/kWh	The actual discharge in the peak segment is based on the subsidy of 0.25 yuan/kWh of the energy storage operator, subsidy for two years
Suzhou City, Jiangsu Province	0.3 yuan/kWh	Energy storage projects in Suzhou Park, the subsidy is 0.3 yuan/kWh, subsidy for three years
Wujiang District, Suzhou City	0.9 yuan/kWh	Suzhou Wujiang District distributed photovoltaic large-scale development implementation plan proposed: operating energy storage project subsidies 0.9 yuan/kWh, subsidy for two years
Zhaoqing City, Guangdong Province	150 yuan/kWh	The one-time subsidy of 150 yuan/kWh, up to 1.5 million yuan
Ningxia	0.8 yuan/kWh	For energy storage projects completed in 2022 and 2023, the charge and discharge times are not less than 300 times, and the subsidy is 0.8 yuan/kWh
Sichuan Province	230 yuan/kW	The annual utilization hours are not less than 600 h, and the subsidy is 230 yuan/kW, up to 1 million yuan, subsidy for three years
Chaoyang District, Beijing	Not more than 20% of the total investment	Subsidies for energy storage projects should not exceed 20% of the total investment
Wuhu City, Anhui Province	0.3 yuan/kWh	The subsidy of 0.3 yuan/kWh, the maximum subsidy of 1 million yuan, the project put into operation before 31 December 2023, the subsidy period of a single project is 5 years
Nanning City, Guangxi Province	0.1 yuan/Wh	The subsidy for power and energy storage batteries is 0.1 yuan/Wh, and the maximum subsidy amount is 11.55 billion yuan
Futian District, Shenzhen	0.5 yuan/kWh	A subsidy of 0.5 yuan/kWh is given to projects with more than 1 million yuan
Hefei City, Anhui Province	0.3 yuan/kWh	0.3 yuan/kWh, for two consecutive years
Tongliang District, Chongqing	0.5 yuan/kWh	0.5 yuan/kWh, for three consecutive years
Wuxi City, Jiangsu Province	0.1 yuan/W	0.1 yuan/W, The maximum limit for a single project is 500 thousand yuan
Inner Mongolia	0.35 yuan/kWh	The discharge allowance for energy storage is 0.35 yuan/kWh, no more than ten years

2.3. The Main Problems of China's PV-ES Integration Subsidy Policy

Reviewing recent subsidy policies for PV-ES integration projects in China, to some extent, presents a favorable scenario. This is because energy storage is an important technology and foundational equipment supporting China's new power system. Its rapid development holds significant implications for optimizing the value of PV-ES integration projects, promoting the green transformation of energy, and facilitating high-quality energy development. By providing subsidies and support, the government encourages continuous innovation and upgrading of energy storage technology to enhance its performance, reduce costs, and propel technological advancements in energy storage. However, due to the insufficient time elapsed for the subsidy policy for PV-ES integration projects in China to fully demonstrate its implementation effects, and the complexity inherent in energy storage technology and markets, evaluating the effectiveness of subsidy policies may necessitate considering multiple factors comprehensively and employing appropriate evaluation methods. Currently, two main issues are evident in China's subsidy policy for PV-ES integration projects:

(1) Insufficient subsidy intensity hampers investment incentives: The current bottleneck restraining industry development remains the cost factor. While the photovoltaic industry has gradually reduced generation costs through years of technological iteration and capacity construction, the mandatory storage requirements for new energy sources are likely to increase the costs of photovoltaic projects, thereby diminishing profitability. Excessive costs could deter investment in PV-ES integration projects, hindering industry development and the establishment of a mechanism for new power installation development based on storage and peak-shifting capabilities. Hence, subsidy policies are indispensable. However, the current subsidies for energy storage mostly range from 0.1 to 0.3 RMB/kWh, with subsidy periods mostly limited to three years. These subsidies are insufficient to cover the investment costs of energy storage facilities, failing to mitigate investment risks for investors or provide stable expected returns, thus struggling to stimulate investment and construction willingness in the capital market. Therefore, the industry also anticipates further subsidy policies or the implementation of market-oriented trading mechanisms to encourage more investors to participate in system construction.

(2) Broad subsidy standards lack targeted measures: Due to the complexity of energy storage technology and markets, the technologies employed and the proportion of energy storage configurations significantly impact the lifecycle costs of PV-ES integration projects. While energy storage subsidy policies typically specify storage ratios ranging from 10% to 20%, some local policies demand high proportions of storage. In situations where energy storage subsidies already struggle to cover the investment costs of energy storage facilities, requiring high proportions of storage means project operators not only fail to generate electricity revenue but also incur losses, resulting in negative internal rates of return. If market conditions are not considered, mandating high proportions of storage for power stations could dampen enthusiasm for capital investment in photovoltaic projects. Therefore, on the basis of reasonably allocating energy storage proportions, it is essential to research and formulate more effective subsidy standards for high-proportion energy storage support, actively explore more suitable subsidy schemes covering the additional costs incurred by energy storage in PV-ES integration projects. With changes in project capacity, policy levels, and energy storage configurations, significant fluctuations in project internal rates of return are expected. Thus, to achieve the desired level of returns, it is necessary to formulate corresponding subsidy standards tailored to different project circumstances.

Policy formulation may be straightforward, but effective evaluation mechanisms are needed during implementation to provide feedback on policy effectiveness, ensuring the efficient utilization of subsidy funds. Therefore, conducting an economic analysis of the implementation effects of China's subsidy policy for PV-ES integration projects is crucial to adjust and improve policies promptly, ensuring they achieve the desired effects and promote the sustainable development of the clean energy industry. Furthermore, amid the current slowdown in the overall Chinese economy, implementing subsidies for PV-ES integration projects can help drive the development of the new energy industry, promote technological innovation and industrial transformation, alleviate energy consumption pressures, spur regional development and employment growth, and facilitate optimization of the energy structure, thereby aiding China's economy in achieving sustainable development.

In summary, from the perspective of photovoltaic storage and energy storage-related subsidy policies, energy storage subsidies constitute an important source of revenue for PV-ES integration projects. Although energy storage technology is becoming increasingly mature, and the prices of major materials are stabilizing, the profitability model and industry standards for energy storage are still unclear, and the impact of subsidy policies is limited. The return on investment in PV-ES integration projects has not been practically verified. Considering the development situation, it is still necessary to stimulate investment and drive industry development by increasing energy storage subsidies. Moreover, the proportion of energy storage configurations also affects the speed and scale of development for new energy sources and energy storage. Therefore, accurately analyzing the lifecycle costs and economic viability of PV-ES integration projects considering energy storage subsidies becomes an urgent issue in need of resolution.

3. Economic Analysis Model of PV-ES Integration

3.1. PV-ES Integration Project Cost and Benefits

Due to the relatively high cost of energy storage deployment and its shorter lifespan compared to other equipment in photovoltaic (PV) projects, energy storage systems (ESS) in PV-integrated projects require multiple updates throughout their lifecycle, leading to an overall increase in costs. However, despite this cost implication, ESS significantly reduce curtailed solar energy, thereby extending the operational hours of PV-integrated projects well beyond those of conventional PV projects. Furthermore, under prevailing electricity market mechanisms, ESS can generate revenue through ancillary services. Given the significant impact of ESS on the cost and benefits of PV projects, an accurate analysis of the economic viability of PV-integrated projects necessitates a comprehensive examination of their cost and benefit composition. To enhance readability, key symbols and explanations thereof are provided in Table 3.

The lifecycle cost of a photovoltaic energy storage (PV-ES) integrated project encompasses all expenses incurred throughout its entire lifecycle, comprising the investment and construction phase, production and operational phase, as well as the decommissioning phase. These expenses include construction costs, operation and maintenance expenses, replacement costs, and applicable taxes (Reference [32]). To ensure a more reasonable and reliable electricity cost per unit for PV-ES integrated projects, aligning them more closely with real-world scenarios, additional costs such as insurance premiums, labor costs, material costs, and other expenses have been integrated into the total cost calculation, building upon the research outlined in Reference [17]. The total cost of a PV-ES integrated project can be expressed as:

$$C_{total} = C_{inv} + C_{OM} + C_{rep} + C_{tax} + C_{ins} + C_{lab} + C_{\mathrm{int}} + C_{rec} + C_{OC} \quad (1)$$

The primary revenue stream of photovoltaic energy storage (PV-ES) integrated projects arises from the synergistic interaction between photovoltaic electricity generation and energy storage systems, encompassing both system electricity generation revenue and ancillary service revenue. System electricity generation revenue comprises photovoltaic electricity generation revenue and revenue from mitigating curtailment through energy storage. By storing energy during periods of high electricity prices and discharging it during periods of low prices, PV-ES integrated projects optimize energy utilization efficiency and enhance revenue. The amount of energy stored by the energy storage system is contingent upon factors such as its capacity, depth of charge and discharge, and cycle count, as dictated by the principles of energy storage operation.

Table 3. Variables and explanations.

Variables	Unit	Symbol Interpretation
C_{total}	10^4¥	Total cost of PV-ES integrated project
C_{inv}	10^4¥	System initial construction cost
C_{OM}	10^4¥	System operation and maintenance costs
C_{rep}	10^4¥	Energy storage replacement cost
C_{tax}	10^4¥	Tax payable
C_{ins}	10^4¥	Insurance expense
C_{lab}	10^4¥	Labor cost
C_{int}	10^4¥	Interest expense
C_{rec}	10^4¥	Cost recovery
C_{OC}	10^4¥	Other costs
I_{total}	10^4¥	Total revenue of PV-ES integrated project
Q_{PV}	kWh	Photovoltaic power generation on-grid electricity
Q_{ES}	kWh	The discarded light power stored in energy storage
P_{grid}	yuan/kWh	The on-grid tariff implemented by the photovoltaic power station
R_A	10^4¥	Energy storage auxiliary services revenue
S_{ES}	-	Energy storage subsidy
E_{total}	kWh	Power generation of PV-ES integrated project
N	year	Life of PV-ES integrated project
r	-	Discount rate
C	MW	Installed capacity of power generation system
H_{total}	hour	Annual utilization hours
o_{μ}	-	Plant rate
η	-	Photovoltaic installed system efficiency
θ_{deg}	-	Component decay rate

Due to variations in local conditions, the emphasis placed on assessment and incentives for photovoltaic power plants outlined in the "Implementation Regulations for Grid-connected Power Plant Operation Management" and the "Implementation Regulations for Ancillary Service Management of Grid-connected Power Plants" differs significantly across regions. Presently, the focus of assessment lies in active power regulation and power forecasting, while incentives center on compensating for the accuracy of short-term power forecasting. The integration of energy storage not only reduces the assessed electricity volume but also provides certain compensation. Consequently, the additional revenue generated by photovoltaic power plants in the ancillary services market constitutes ancillary service revenue. The net settlement cost for ancillary services represents the compensation income obtained for providing ancillary services, subtracting the assessment cost expenditure. However, since this portion of electricity is not derived from actual electricity generation, it is not included in the cumulative electricity generation and is solely utilized for calculating cash inflows and tax liabilities.

Furthermore, during the operational phase of PV-ES integrated projects, the revenue derived from energy storage subsidies has become increasingly important for operators. The total revenue of PV-ES integrated projects can be expressed as:

$$I_{total} = (Q_{PV} + Q_{ES}) \times P_{grid} + R_A + S_{ES} \tag{2}$$

The forms of energy storage subsidies are diverse, encompassing initial investment subsidies, discharge capacity subsidies, installed capacity subsidies, among others. The design of subsidy mechanisms influences the feasibility and economic viability of system investments. Initial investment subsidies refer to one-time financial support provided by the government upon the completion of construction of photovoltaic energy storage (PV-ES) integrated projects. Discharge capacity subsidies, on the other hand, are subsidies provided based on the selling price of electricity generated by the system. Installed capacity subsidies may be linked to the installed capacity of the system, encouraging the development of larger-scale systems. The recipients of energy storage subsidies also impact economic viability. Subsidies may target different types of users, including residential, commercial, or public institutions. Different user groups exhibit disparities in energy demands, electricity consumption patterns, and economic conditions, which in turn influence the investment returns of PV-ES integrated projects.

3.2. The PV-ES Integration Project LCOE Model

Levelized cost of electricity (LCOE) is an internationally recognized method for evaluating the costs of various electricity generation technologies. It entails the economic assessment of dividing the total costs of constructing and operating electricity-generating assets over their lifetimes by the total energy output of the assets during that lifespan [33]. Because its fundamental principle rests on the equivalence of the net present value of costs and the net present value of revenues over the system's lifecycle, costs and electricity generation for PV-ES integrated projects should be discounted first. Subsequently, the resulting electricity generation costs, with the discount rate set as the expected rate of return, represent the theoretical minimum unit energy price the system can accept. The general equation for LCOE is provided in Equation (3).

$$LCOE = (\sum_{n=0}^{N} \frac{C_{\text{total}}}{(1+r)^n})/(\sum_{n=0}^{N} \frac{E_{\text{total}}}{(1+r)^n}) \quad (3)$$

To enhance the rationality and reliability of the electricity cost per kilowatt-hour (kWh) for photovoltaic energy storage (PV-ES) integrated projects, this study integrates the lifecycle cost of PV-ES integrated projects and the efficiency of the equipment to construct a PV-ES integrated LCOE model. Furthermore, the model incorporates the efficiency of the photovoltaic (PV) installation system and the component degradation rate when calculating electricity generation, rendering it more applicable to PV-ES integrated projects. In summary, the improved model can be expressed as follows:

$$LCOE = [\sum_{n=0}^{N} \frac{C_{inv} + C_{OM} + C_{rep} + C_{tax} + C_{ins} + C_{lab} + C_{\text{int}} + C_{rec} + C_{OC}}{(1+r)^n}]/[\sum_{n=0}^{N} \frac{C \times H_{total} \times (1-o_{\mu})_n \times \eta \times (1-\theta_{\text{deg}})^n}{(1+r)^n}] \quad (4)$$

3.3. LCOE-NPV System Dynamics Model

System dynamics is a methodology for addressing complex system issues [34], which has been maturely applied in various aspects within the field of power systems, such as demand response resource efficiency evaluation [35], system dynamic effects assessment [36], visual analysis of complex systems [37], and analysis of incentive mechanisms for renewable energy [38]. Further analyzing the characteristics of Levelized Cost of Energy (LCOE) in photovoltaic-energy storage (PV-ES) integrated projects, the inclusion of energy storage in PV-ES integrated projects serves to reduce curtailed solar energy and provide grid ancillary services. Coupled with specific subsidies, this distinguishes the revenue model of PV-ES integrated projects from traditional photovoltaic power plants, resulting in significant differences in electricity generation, construction costs, operating costs, and tax contributions. Additionally, throughout the lifecycle of PV-ES integrated projects, the incorporation of energy storage substantially increases project costs, with the replacement cost of energy storage exhibiting a dynamic downward trend. This dynamic fluctuation in total costs throughout the lifecycle subsequently leads to significant variations in the project's LCOE. The transmission mechanism of the impact of replacement cost changes on LCOE is a dynamic long-term accumulation and adjustment process, with its effects evolving over time. In summary, the calculation of LCOE in PV-ES integrated projects involves numerous dynamic factors that interact with each other. Consequently, the LCOE of PV-ES integrated projects fluctuates dynamically throughout their lifecycle, rendering it a complex dynamic system. Given that system dynamics possesses certain advantages in analyzing the temporal trends of complex systems [39], it can not only visually depict the interactions among various complex elements but also employ a combination of qualitative and quantitative methods to model and simulate systems with multiple information and causal feedback. Moreover, it holds advantages in addressing cyclical and long-term issues. Therefore, to fully identify the internal and external factors affecting cost stabilization and subsequently analyze the impact of these factors on the LCOE of PV-ES integrated projects, a causal relationship model of PV-ES integrated project LCOE is established based on the electricity generation and cost composition of such projects, utilizing system dynamics methodology. As shown in Figure 3, '+' indicates a positive proportional relationship between factors, '-' indicates a negative proportional relationship between two factors, and variables within '< >' denote shadow variables, which are equivalent in meaning to the variables in the figure.

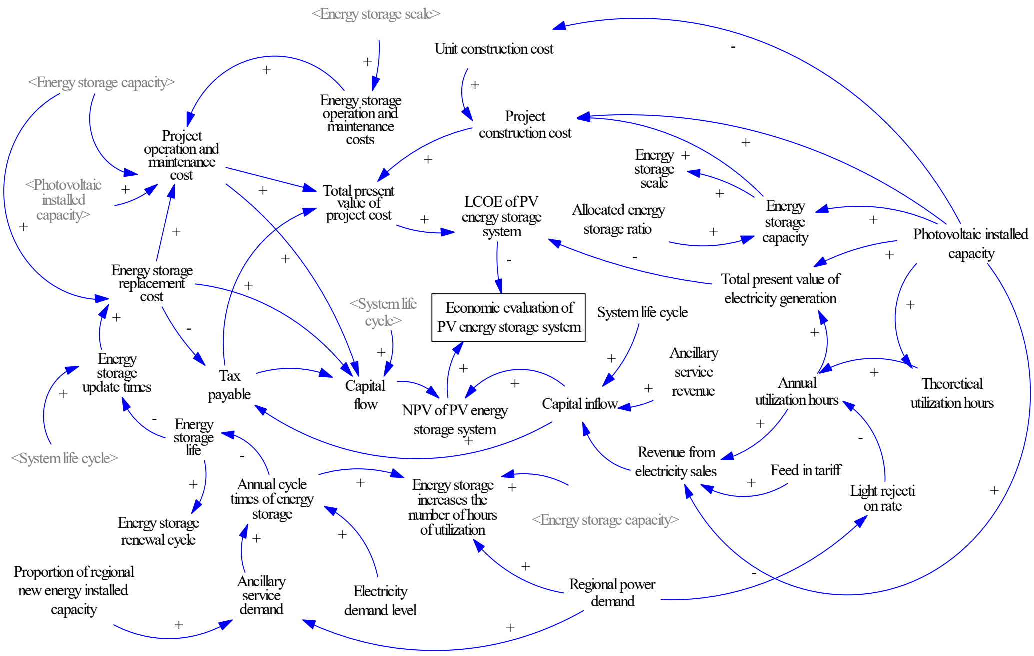

Figure 3. Causal diagram of factors affecting the economy of PV-ES integration project.

Based on Figure 3, it is evident that, at a constant level of electricity demand, the incorporation of energy storage significantly enhances the electricity generation of photovoltaic projects. Consequently, while project revenue from electricity sales increases, the corresponding tax obligations also rise. Furthermore, the integration of a certain capacity of energy storage not only directly elevates the construction and operation costs of the project but also entails multiple updates of the core components of the energy storage equipment throughout the project lifecycle. The output tax on these materials can be offset against the input tax. Consequently, compared to conventional photovoltaic projects, the calculation of tax obligations for photovoltaic energy storage projects is more intricate.

Based on the causal relationship analysis of the integrated photovoltaic (PV) and energy storage (ES) levelized cost of electricity (LCOE) system, combined with the construction cost composition, operation and maintenance cost composition of the integrated PV-ES projects, and the current tax system, considering the characteristics of integrated PV-ES project construction, a dynamic model of LCOE system for integrated PV-ES projects is constructed, as shown in Figure 4. Although LCOE can intuitively reflect the cost level of the entire lifecycle of the system and to a certain extent characterize the profitability of the project, it can be observed from Equation (2) that this indicator calculation cannot fully reflect the impact of certain benefits on the overall profitability of the project. Therefore, the LCOE indicator cannot be used to compare the economic effects of different energy storage subsidy standards on integrated PV-ES projects, and internal rate of return (IRR) and net present value (NPV) should still be used as evaluation indicators for energy storage subsidy standards. The internal rate of return is the discount rate when the net present value (NPV) of the project equals 0.

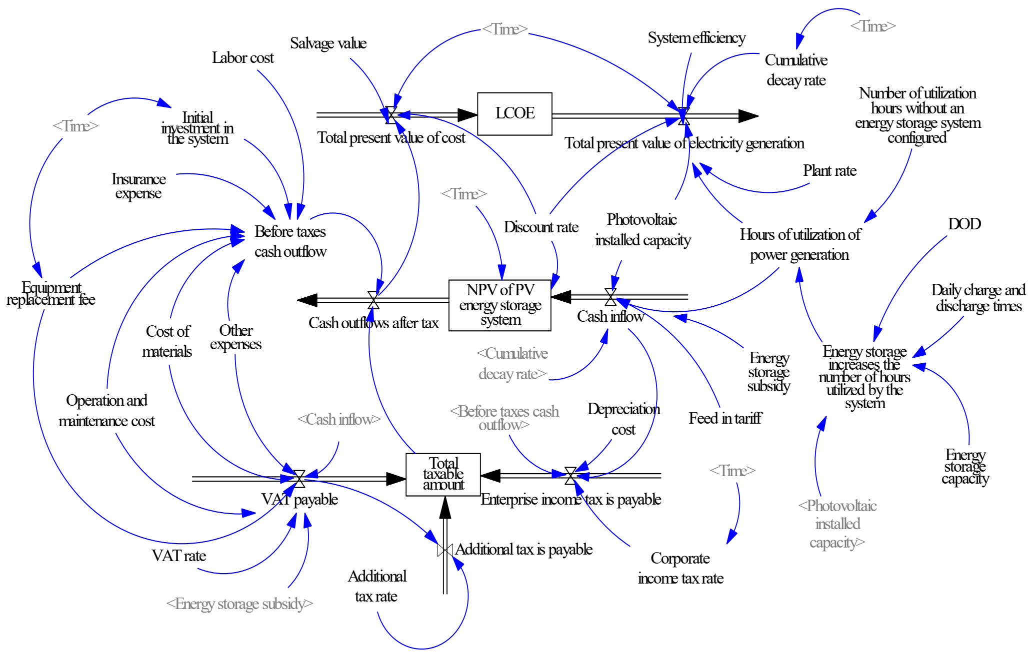

Figure 4. LCOE inventory flow diagram of PV-ES integration project.

The integrated PV-ES project LCOE-NPV model constructed in this paper consists of four subsystems: LCOE system, NPV system, pre-tax cash outflow, and total taxable amount. The logical relationship between the subsystems is as follows: the LCOE system can calculate the annual electricity generation and the present value of the lifecycle electricity generation, combined with parameters such as grid electricity price to calculate the cash inflow for each year; the pre-tax cash outflow system sums up the expenditures for each year separately, and the tax payable system calculates the various tax amounts payable by the project based on the income and some expenditures of the project and sums up to obtain the total taxable amount; using the total taxable amount and pre-tax cash outflow, the post-tax cash outflow for each year can be calculated; based on the post-tax cash outflow for each year and the present value of the lifecycle electricity generation, the LCOE of the project can be calculated. On the one hand, the investment during the project construction phase, annual operation and maintenance costs, and taxable amounts are summarized, and these data are accumulated and discounted in the cost present value of the LCOE subsystem; on the other hand, by adjusting the discount rate to calculate the internal rate of return of the project, comparing it with the industry average, and judging whether the project's profit level meets expectations. The main variables set in the integrated PV-ES LCOE-NPV dynamic model are shown in Table 4.

Table 4. The main parameter setting of the LCOE-NPV system dynamics model of PV-ES integration project.

Name of a Variable	Type of Variable	Unit
LCOE	Auxiliary variable	yuan/kWh
Total present value of cost	State variable	10^4 ¥
Cash outflows after tax	Auxiliary variable	10^4 ¥/year
Pre-tax cash outflow	Auxiliary variable	10^4 ¥/year
Total taxable amount	Auxiliary variable	10^4 ¥/year
Total present value of electricity generation	State variable	kWh
NPV	State variable	10^4 ¥
Cash inflow	Auxiliary variable	10^4 ¥/year

4. Case Study

4.1. Initial Data and Parameter Settings

Currently, the service life of photovoltaic (PV) modules generally ranges between 25 and 30 years. According to the 2022 National Standard of the Ministry of Housing and Urban-Rural Development of China, titled "General Specification for Building Energy Conservation and Renewable Energy Utilization", the design service life of PV power plants should exceed 25 years, with a maximum power attenuation of PV modules not exceeding 20% within 25 years. This study takes a solar energy storage project in western Inner Mongolia Autonomous Region, China, as an example, conducting simulation and emulation based on the year 2022 as the baseline year, with a time step of 1 year and a simulated time frame of 25 years.

The annual maximum equivalent full-load hours of solar energy in the region is approximately 1750 h, with a PV installed capacity of 100 MW. Utilizing the 2022 national average conditions as model input parameters, assuming a plant construction cost of 3.4 yuan per watt, the total investment for the case project is estimated to be 340 million yuan. Based on operational experience, operation and maintenance (O&M) expenses, including material costs, repair costs, and other expenses, are calculated at 0.4% of the fixed assets of the system, while engineering insurance expenses are calculated at 0.2%. Value-added tax is set at 13%, surtax at 6%, and income tax at 25%, with the implementation of the "Three Exemptions and Three Halves" policy. According to the regulations of the National Energy Administration on the conduct of market-oriented transactions for new energy sources nationwide, it is assumed that 10% of the projected current electricity production from the project participates in market-oriented transactions. Additionally, based on the summary table of operation and settlement of photovoltaic power plants published by the Mengxi Power Grid in 2020, the assessment electricity volume and auxiliary service fees for the case project are calculated.

In accordance with the requirements of the Inner Mongolia Autonomous Region Energy Bureau regarding the integration of energy storage in new energy power generation, it is necessary to ensure that the configured capacity reaches 5% of the construction scale, with a minimum energy storage duration of 1 h. Considering the installed capacity of the case project, the standard configuration involves allocating 5% of the installed capacity (5 MW/5 MW·h) for energy storage. Based on the average bid price for lithium iron phosphate energy storage systems for frequency regulation in 2022, assuming an engineering total contracting model, the cost of the energy storage system is set at 1.56 yuan/Wh. Regarding the replacement cost of energy storage facilities, factors such as technological innovation and future cost reductions need to be considered. It is assumed that the electrochemical energy storage cells are replaced every 8 years, with a total of three replacements during the lifecycle. The unit costs for the three replacements are 1.3 yuan/Wh, 1.2 yuan/Wh, and 1.0 yuan/Wh, respectively.

This study employs the scenario of a photovoltaic power station without energy storage as the baseline. The standard configuration involves allocating 5% of the installed capacity (5 MW/5 MW·h) for energy storage. Additionally, configurations of 10% and 15% are considered for comparative analysis. The study evaluates the changes in levelized cost of electricity (LCOE) and internal rate of return (IRR) before and after altering the configuration proportions to assess their economic feasibility. Subsequently, the impact of energy storage subsidies on the economic viability of the integrated solar and energy storage station is considered. Considering possible future policy scenarios post energy storage configuration, the study takes into account potential government subsidies for energy storage participation in new energy consumption, including subsidy methods, intensity, and duration. It is assumed that the project can utilize initial investment subsidies or discharge-based subsidies to meet the energy storage subsidy requirements. Six combination scenarios (Table 5) are defined to simulate the evolution of LCOE for the integrated solar and energy storage station over the next 25 years, considering factors such as energy storage configuration, presence of energy storage subsidies, subsidy methods, subsidy intensity, and subsidy duration.

Table 5. Simulation scenario.

Scenario	Configure or Not Energy Storage	Energy Storage Allocation Ratio	Have or Not Subsidy	Subsidy Method	Subsidy Intensity
1	No	/	/	/	/
2	Yes	5% 10% 15%	No	/	/
3	Yes	10%	Yes	Initial investment allowance	10% 20% 30%
4	Yes	10%	Yes	Discharge allowance	0.2 yuan/kWh 0.3 yuan/kWh 0.4 yuan/kWh
5	Yes	15%	Yes	Initial investment allowance	10% 20% 30%
6	Yes	15%	Yes	Discharge allowance	0.2 yuan/kWh 0.3 yuan/kWh 0.4 yuan/kWh

4.2. Analysis of Simulation Results in Different Ways

4.2.1. Energy Storage Configuration Ratio Scenario

According to the bulletin released by the National Energy Administration's official website regarding the monitoring and evaluation results of renewable energy electricity development nationwide in 2022, the average photovoltaic utilization rate in the western region of Inner Mongolia was determined to be 97.4% for the year. During the period from January to March, the maximum curtailment rate reached 5.2%. Assuming a curtailment of 5% of the installed capacity for the project, the regional solar annual utilization hours of 1616 h in 2022 are considered as the baseline. The benchmark electricity price for thermal power in western Inner Mongolia is set at 0.2829 ¥/(kW·h) as the grid electricity price. Using the previously established LCOE-NPV dynamic system model, simulations are conducted for both scenarios: without energy storage configuration and with alternative energy storage configurations. By adjusting the discount rate within the model to equate the NPV to zero, the internal rate of return for each scenario is calculated, as illustrated in Table 6.

Table 6. Energy storage allocation ratio and internal rate of return.

Energy Storage Allocation Ratio	IRR
No energy storage	8.14%
5%	7.12%
10%	6.36%
15%	5.67%

According to Table 6, it is evident that when photovoltaic (PV) power plants are not equipped with energy storage, the internal rate of return (IRR) exceeds 8%, which is generally considered indicative of favorable economic viability. However, in scenarios where energy storage is incorporated without considering energy storage subsidies, the IRR of integrated solar and storage projects experiences a significant decline. This reduction is noteworthy as it substantially diminishes the IRR compared to the situation without storage. Moreover, the inclusion of energy storage escalates the initial investment costs, leading to a noticeable decrease in IRR with an increase in the proportion of energy storage configuration. The current study posits that, at the present juncture, a substantial allocation of energy storage may compromise the economic advantages of PV power generation. The enthusiasm for integrating storage with solar power plants is not high, and the inclusion of energy storage could reduce the overall IRR of the facility to below the critical threshold of 8%. In the current case study, the minimum proportion of energy storage configuration results in a significant 1.02 percentage points reduction in IRR.

Given the calculated IRR values, the trends in levelized cost of electricity (LCOE) for the project are simulated under four scenarios, as depicted in Figure 5. In Figure 5, the differences in LCOE among the four scenarios are relatively small, and all LCOE values are below the benchmark electricity price for thermal power. In comparison to scenarios with energy storage, the initial construction and equipment maintenance costs in the no-storage scenario are lower, leading to a considerably lower LCOE level, particularly in the mid to late stages of the project's lifecycle. The LCOE in the no-storage scenario is 0.17 CNY/kWh, significantly below the thermal power benchmark electricity price of 0.2829 CNY/kWh. This outcome suggests that scaling up development can provide a substantial cost advantage for PV power projects in the region.

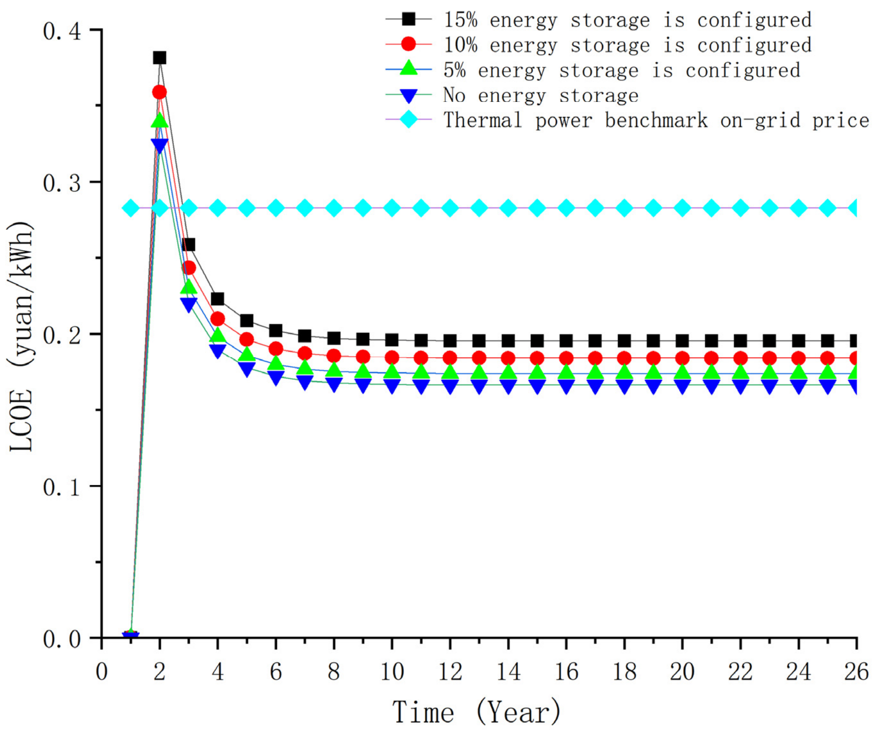

Figure 5. The LCOE trend of different energy storage configuration ratios.

Presently, investors generally seek internal rates of return ranging from 7% to 8% for solar and storage grid-connected projects. From the calculated IRRs for various scenarios, it is evident that the case project is economically viable under the standard energy storage scenario. However, PV-ES integration projects with a high proportion of energy storage are likely to struggle to achieve the anticipated returns. In order to promote the absorption of renewable energy, reduce regional curtailment levels, enhance the end-use efficiency of new energy, and alleviate cost pressures faced by solar and storage integration, several regions in the country have implemented mandatory storage integration policies. Additionally, subsidies for energy storage, mainly in the form of initial investment and discharge capacity subsidies, have been introduced.

4.2.2. Energy Storage Subsidy Scenario

According to the data in this case, the co-installation of energy storage projects with a capacity of 5–15% for photovoltaic power stations results in an initial investment increase of 2.3–6.9%. The internal rate of return decreases by 1–2%. The compulsory large-scale co-storage implies that investors not only fail to achieve expected returns but may also bear a certain proportion of losses. For investors, economic viability takes precedence over policy-driven initiatives and technological innovations. Only projects that ensure anticipated returns hold investment value. Typically, photovoltaic development enterprises seek an expected return rate of 7% or higher for investing in PV-ES integration projects. Based on the principles of the net present value (NPV) calculation, setting the discount rate to the internal rate of return of the project (7%) when the NPV equals zero. Under the two energy storage configuration ratios mentioned earlier that fall short of the internal rate of return standards, altering energy storage subsidy methods and subsidy intensities can be explored. This is performed to observe whether the NPV of the PV-ES integration project is greater than zero, thereby determining if it can achieve the anticipated economic benefits of 7%. Considering the current situation of wasted solar energy in the project location, assuming that energy storage configuration can reduce wasted solar energy by 5% or less, the contribution of energy storage regulation is expressed as the increased electricity generation of the PV-ES integration project, quantifiable through additional utilization hours.

(1) Scenario of subsidizing 10% energy storage configuration

Figure 6 illustrates that with a 10% energy storage configuration, the net present value of the project increases with the intensification of subsidy levels. However, only when the energy storage subsidy intensity reaches 30% of the initial investment can the project achieve a 7% internal rate of return. Below a subsidy intensity of 30%, the expected return rate cannot be attained, jeopardizing investor interests. This lack of enthusiasm among investors hinders the sustainable development of photovoltaic and energy storage systems. Figure 7 shows that even with the maximum discharge subsidy of 0.4 yuan/kWh, the project struggles to achieve a 7% return on investment. Due to the limited range of additional electricity generated by energy storage, the impact of discharge subsidies during the operational period on improving project investment returns is constrained, making it difficult to cover the investment costs of energy storage.

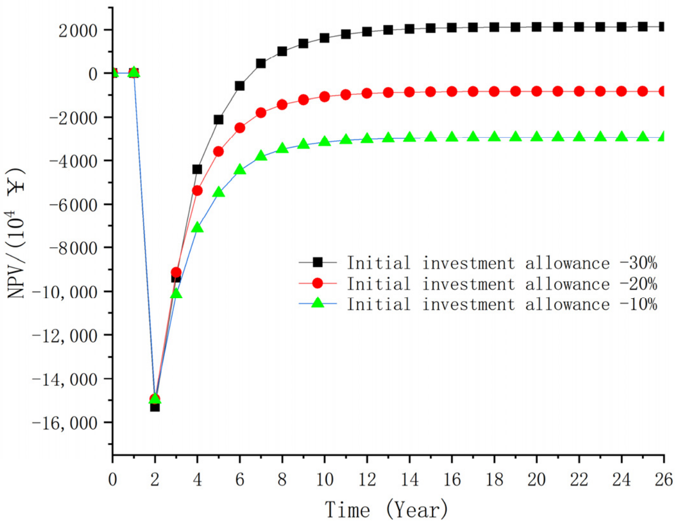

Figure 6. NPV trend of 10% energy storage under different initial investment subsidy ratio.

(2) Scenario of subsidizing 15% energy storage configuration

Figures 8 and 9 illustrates that, under the configuration with a 15% energy storage ratio, whether in terms of initial investment subsidies or discharge capacity subsidies, the system struggles to achieve a return on investment of 7%, even with maximum subsidy intensity. The significant increase in project cost resulting from the high proportion of energy storage renders conventional energy storage subsidy policies insufficient to cover the investment costs associated with energy storage. Consequently, the economic viability of photovoltaic energy storage integrated projects is currently not evident. At this point, the mandatory promotion of photovoltaic energy storage integration also hinders the resolution of challenges related to the integration of new energy sources.

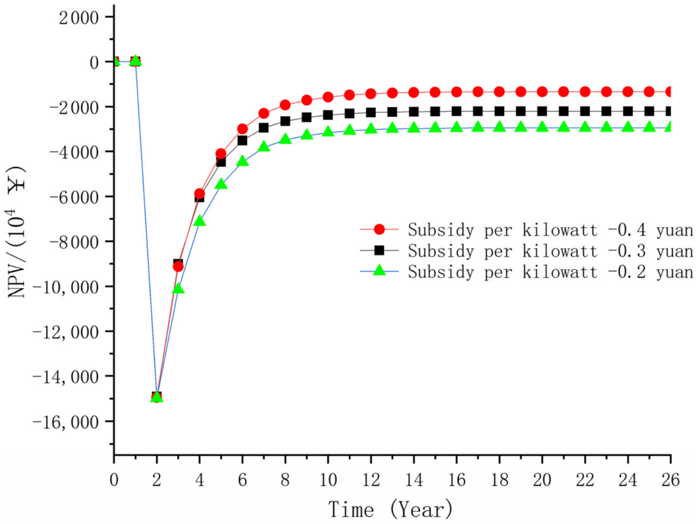

Figure 7. NPV trend of 10% energy storage under different discharge subsidy standards.

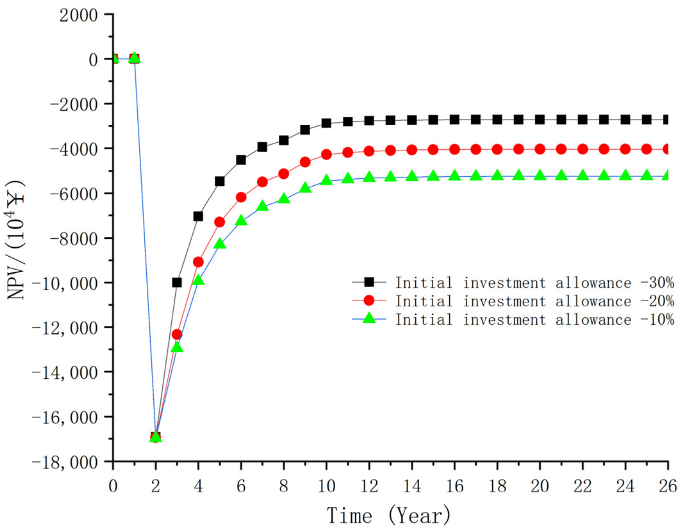

Figure 8. NPV trend of 15% energy storage under different initial investment subsidy ratio.

The simulation results above suggest that while the currently implemented energy storage subsidy policies positively promote PV-ES integration projects, they inadequately cover the investment costs of energy storage, thus failing to stimulate the proactive participation of capital markets in the construction of PV-ES integration projects. For PV-ES integration projects plants, although high-proportion initial investment subsidies can significantly alleviate the initial investment burden of system construction, making it easier for investors to achieve investment returns in the later stages of construction and shortening the time to achieve levelized costs, high-proportion investment subsidies can increase government fiscal pressure, which is detrimental to the healthy development of the industry. While discharge volume subsidies directly impact the operational income of PV-ES integration projects—i.e., the additional subsidy income obtained for every kilowatt-hour of electricity generated during the system's operational period—the current level of discharge subsidies is weak, and their impact on levelized costs is not significant. Moreover, most energy storage subsidies currently have clear subsidy deadlines and maximum limits, which can provide some short-term income supplements. However, as the operational period of integrated photovoltaic and energy storage plants exceeds 20 years, long-term profitability still relies on more market mechanisms. If other market mechanisms are lacking, the incentive effects of subsidy policies on project development are limited. Therefore, in the future, governments can explore more subsidy policies in the temporal dimension and actively promote the implementation of more market-oriented transaction mechanisms, gradually clarifying the cost diversion mechanisms and value compensation mechanisms of PV-ES integration projects. The current cost dilemma faced by PV-ES integration projects is a common problem encountered by emerging industrial tracks. With technological innovations and scale enhancements, the levelized cost of PV-ES integration projects will gradually decrease, reflecting their economic benefits, which will be conducive to the market-oriented sustainable development of such projects.

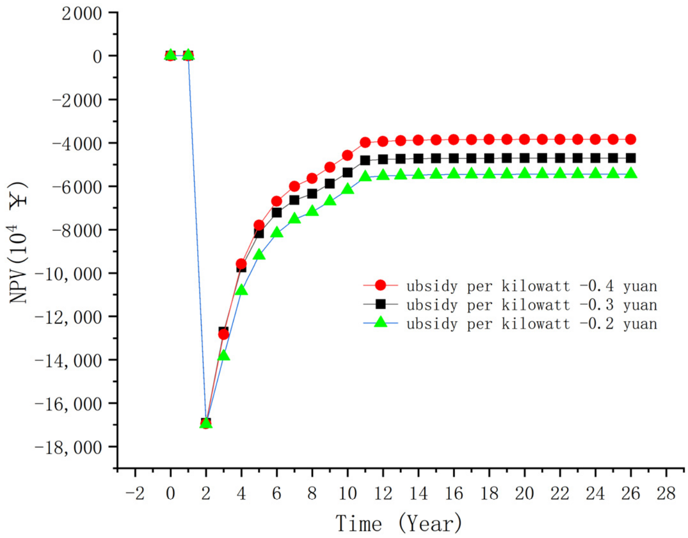

Figure 9. NPV trend of 15% energy storage under different discharge subsidy standards.

5. Conclusions

Compared to traditional photovoltaic (PV) stations, the integration of energy storage in photovoltaic energy storage (PV-ES) stations introduces variables into the project's levelized cost of electricity (LCOE) due to the presence of energy storage equipment upgrades and the incorporation of storage's profit model during operation, which dynamically changes over the project lifecycle. To accurately assess the LCOE of PV-ES stations and subsequently analyze the impact of energy storage subsidies on these stations, this study first outlines the relevant policies in the Chinese PV-ES market. Subsequently, considering the various costs and benefits associated with PV-ES integration projects, and based on the causal relationships affecting their LCOE-related factors, a PV-ES integrated LCOE-NPV dynamic model is constructed. Finally, using a PV-ES project in Inner Mongolia Autonomous Region, China, as a case study, the internal rate of return of PV-ES projects under different energy storage configuration ratios is measured. Additionally, the LCOE over the entire lifecycle under different subsidy scenarios is simulated, analyzing the economic feasibility of PV-ES projects under various energy storage standards. The results indicate that while current energy storage subsidies positively promote projects, the substantial increase in system costs due to energy storage configuration weakens the coverage of cost increases by PV stations even after considering energy storage subsidy factors, thereby failing to stimulate capital markets' enthusiasm for PV-ES integration. Therefore, rational energy storage capacity allocation and optimization of corresponding subsidy policies are essential prerequisites for improving the economic viability and widespread promotion of PV-ES integration projects. The model constructed in this study can intuitively reflect the variation in PV-ES project LCOE over the entire lifecycle, compare different energy storage configuration ratios, and, when combined with NPV indicators, assess the effectiveness of energy storage subsidy policies, providing a new solution for dynamically evaluating the economic feasibility of PV-ES integration projects and promoting their healthy and sustainable development.

6. Policy Implications

Based on the above conclusions, energy storage subsidies play a crucial role in the economic viability of photovoltaic (PV) and energy storage integration projects. Through comprehensive analysis of levelized cost of energy (LCOE), energy storage allocation ratios, and subsidy mechanisms, several insights can be gleaned to guide governments in formulating more specific and effective policies to promote the sustainable development of PV and energy storage integration projects.

Firstly, it is necessary to establish reasonable ratios for PV-to-storage allocation. Excessively high ratios can adversely affect the economic feasibility of PV and storage plants, dampening investor enthusiasm for PV investments and limiting the scale of energy storage deployment. Conversely, excessively low ratios can constrain PV growth due to factors such as limited grid flexibility and insufficient reliable generation capacity. Therefore, a well-designed subsidy policy for energy storage is essential to realize the synergistic development of renewable energy and energy storage.

Secondly, subsidy standards for PV plants with high proportions of energy storage should be tailored to specific storage schemes. Even under current policies with relatively high subsidy levels, high-proportion energy storage schemes may fail to achieve a 7% internal rate of return (IRR) without appropriate subsidies covering the additional costs incurred by energy storage in PV integration projects. Project IRR may fluctuate significantly with changes in project capacity, policy levels, and energy storage configurations, necessitating the formulation of corresponding subsidy standards based on different project conditions to achieve the desired returns.

Thirdly, initial investment subsidies for energy storage can reduce the initial capital costs of PV and energy storage integration projects, enhancing system feasibility. Initial investment subsidies, provided in the form of post-construction incentives, can alleviate investor burdens and encourage greater participation in PV and energy storage integration projects. This is crucial for facilitating the rapid deployment and widespread adoption of PV and energy storage systems, particularly during the initial stages when system costs are relatively high. Additionally, discharge volume subsidies directly impact system economics by increasing revenue per unit of energy generated during system operation, providing investors with more flexible and direct incentives. However, caution is advised in setting discharge volume subsidies to ensure that they stimulate system construction while maintaining fiscal sustainability.

Moreover, extending subsidy periods appropriately may positively impact investment returns. As most current energy storage subsidies have relatively short durations, their incentivizing effect on the development of PV and energy storage integration projects is limited. Long-term subsidy periods can offer investors more stable expected returns, reducing investment risks and encouraging greater participation in project construction. Nevertheless, subsidies should only serve as initial catalysts and incentives for technological innovation in the early stages of development. As the energy storage industry matures, reliance on subsidies should be gradually reduced to avoid stagnation in technological progress and overcapacity. Governments should adjust subsidy policies timely to encourage the industry to follow a healthy development path through technological innovation and rational cost reduction in the supply chain.

This paper proposes a preliminary framework for systematically evaluating the life-cycle cost of photovoltaic and energy storage integrated projects, balancing the impact of energy storage subsidies across different energy storage configuration scenarios. Investors and operators can apply this framework to assess the economic feasibility of projects based on their specific circumstances. When designing subsidy policies, governments need to comprehensively consider multiple factors such as cost, revenue, subsidy methods, and recipients, and make decisions based on sufficient data.

The research program of this paper has strong popularization value, the research method is scientific and reasonable, the data source is real and reliable, and it can provide new ideas and directions for the follow-up research of other optical storage projects and even other new energy distribution and storage projects. Currently, energy storage costs are relatively high. In comparison, photovoltaic and energy storage integrated projects have lower unit construction costs and longer lifespans. In northern China, photovoltaic power generation is more economically viable. Considering the configuration ratio of energy storage equipment and subsidy policies, combined with the future development of new energy in the "Three North" regions, the economic analysis of photovoltaic and energy storage integration has high promotional value. It is recommended to prioritize the consideration of integrated projects with an energy storage configuration ratio of 10% and an initial investment subsidy of 30% for energy storage. Only through scientific and reasonable economic and policy analysis can the development potential of photovoltaic and energy storage integration projects be better stimulated, promoting their widespread application.

One limitation of this framework is the lack of thorough exploration of the impact of phased marketization of renewable energy on project costs and benefits. As a preliminary framework, this study can be further developed to expand the scope of influencing factors, including various elements such as the design process of PV plants and factors affecting economic feasibility in the phased marketization of renewable energy, such as the form of support structures for PV components [40], different installation angles [41], increased height of PV modules above ground, and rear-end gains. Different design approaches at each stage of the project can lead to changes in construction and operational costs, thereby affecting project economics [42]. Particularly, the scale of phased marketization of renewable energy should be considered. This paper only considers the impact of the phased marketization of renewable energy on the participation of 10% of the expected current period electricity of guided renewable energy projects by the National Energy Administration of China. However, the various benefits and costs brought by the gradual participation of renewable energy in the electricity market will also affect the LCOE of the project and should be included [43]. Therefore, the value of energy storage subsidies varies according to the stage of marketization of renewable energy. Future work is suggested to incorporate the influence of phased marketization of renewable energy on the scale and path of the project into the lifecycle measurement framework.

Author Contributions: Conceptualization, R.L.; Methodology, R.L.; Software, R.L.; Formal analysis, W.Z.; Investigation, W.Z.; Resources, S.Z.; Data curation, R.L.; Writing—original draft, R.L.; Writing—review & editing, W.Z.; Supervision, W.Z.; Project administration, W.Z. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge the National Key Research and Development Program of China (Grant No. 2022YFE0207700).

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Shuan Zhu was employed by the company Shanghai Qiyuan Green Power Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Ministry of Ecology and Environment of China. China's Climate Change Policy and Action 2023 Annual Report [R/OL]]. (2023-10-27)[2024-02-19]. Available online: https://www.mee.gov.cn/ywgz/ydqhbh/wsqtkz/202310/W020231027674250657087.pdf (accessed on 19 February 2024).
2. Wang, F.; Quan, L.; Cong, L.; Lu, M. Economic benefits of distributed photovoltaic power generation under different operating modes in situation of subsidy reduction: A case of Beijing-Tianjin-Hebei. *J. Arid. Land Resour. Environ.* **2024**, *38*, 87–94.

3. Wang, J.; Lin, Y.; Wu, C.; Yang, B. Current situation and development of solar photovoltaic industry under the background of carbon neutrality. *Energy Storage Sci. Technol.* **2022**, *11*, 731–732.
4. Zhang, Y.; Huang, B. Cost analysis and policy suggestions of China's new energy development. *Electr. Power* **2018**, *51*, 10–15.
5. Varma, R.K.; Salama, M. Large-scale photovoltaic solar power integration in transmission and distribution networks. In Proceedings of the 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 24–28 July 2011; pp. 1–4. [CrossRef]
6. Choudhury, S. Review of energy storage system technologies integration to microgrid: Types, control strategies, issues, and future prospects. *J. Energy Storage* **2022**, *48*, 103966. [CrossRef]
7. Peng, T.; Zhang, Y.; Zhao, J. Distributed Energy Storage Cluster Control Method for DC Microgrid Considering Flexibility. *Math. Probl. Eng.* **2022**, *2022*, 6761595.
8. Rekioua, D.; Kakouche, K.; Babqi, A.; Mokrani, Z.; Oubelaid, A.; Rekioua, T.; Azil, A.; Ali, E.; Alaboudy, A.H.K.; Abdelwahab, S.A.M. Optimized Power Management Approach for Photovoltaic Systems with Hybrid Battery-Supercapacitor Storage. *Sustainability* **2023**, *15*, 14066. [CrossRef]
9. Bayod-Rújula, Á.A.; Tejero-Gómez, J.A. Analysis of the Hybridization of PV Plants with a BESS for Annual Constant Power Operation. *Energies* **2022**, *15*, 9063. [CrossRef]
10. Weng, S.; Ma, T.; Kanzumba, K.; Zhao, F.; Zhang, Y.; Li, B.; Xue, P. Battery capacity design and optimal operation control of photovoltaic-battery system considering electrochemical aging. *J. Energy Storage* **2024**, *79*, 110103. [CrossRef]
11. Coppitters, D.; De Paepe, W.; Contino, F. Robust design optimization and stochastic performance analysis of a grid-connected photovoltaic system with battery storage and hydrogen storage. *Energy* **2020**, *213*, 118798. [CrossRef]
12. Chen, G.; Yuan, Y.; Fu, Z. Application of storage battery to restrain the photovoltaic power fluctuation. *Proc. CSU-EPSA* **2014**, *26*, 27–31.
13. Hodge, B.M.; Martinez-Anido, C.B.; Wang, Q.; Chartan, E.; Florita, A.; Kiviluoma, J. The combined value of wind and solar power forecasting improvements and electricity storage. *Appl. Energy* **2018**, *214*, 1–15. [CrossRef]
14. Lakhain, R.; Doluweera, G.; Bergerson, J. Internalizing land use impacts for life cycle cost analysis of energy systems:A case of California photovoltaic implementtation. *Appl. Energy* **2014**, *116*, 253–259. [CrossRef]
15. Hin, J.N.C.; Zmeureanu, R. Optimization of a residential solar combisystem for minimum life cycle cost, energy use and exergy destroyed. *Sol. Energy* **2014**, *100*, 102–113.
16. Perez, M.; Perez, R.; Rábago, K.R.; Putnam, M. Overbuilding & curtailment: The cost-effective enablers of firm PV generation. *Sol. Energy* **2019**, *180*, 412–422.
17. Wen, J.; Liu, N.; Pei, J.; Xu, R.; Liu, D. Life cycle cost analysis for energy storage technology. *Therm. Power Gener.* **2021**, *50*, 24–29.
18. Zhao, X.; Wang, Z. Technology, cost, economic performance of distributed photovoltaic industry in China. *Renew. Sustain. Energy Rev.* **2019**, *110*, 53–64.
19. Dunhu, C.; Chuan, T.; Zeyang, Z.; Qi, M.; Kuang, Y.; Liming, H. Economic benefit analysis on photovoltaic power generation with LCOE model: The case of poverty alleviation project in rural area of Yichang city. *Res. Environ. Sci.* **2020**, *33*, 2412–2420.
20. Pan, B.B.; Chen, Z.H.; Jia, N.F.; Li, Y.H.; Hao, Y. Research on cost accounting of photovoltaic power generation-Analysis based on LCOE method. *Price Theory Pract.* **2019**, *05*, 138–140+144.
21. Wang, J.Y.; Zhou, B.R.; Wu, W.; Zheng, M.; Lu, S.; Yao, W.; Zhao, W. Levelized cost of energy of centralized photovoltaic power in western China and distributed photovoltaic power in eastern China. *South. Power Syst. Technol.* **2020**, *14*, 80–89.
22. Jacob, R.; Riahi, S.; Liu, M.; Belusko, M.; Bruno, F. Technoeconomic Impacts of Storage System Design on the Viability of Concentrated Solar Power Plants. *J. Energy Storage* **2021**, *34*, 101987. [CrossRef]
23. Schmidt, O.; Melchior, S.; Hawkes, A.; Staffell, I. Projecting the Future Levelized Cost of Electricity Storage Technologies. *Joule* **2019**, *3*, 81–100. [CrossRef]
24. Lv, S.; Cai, S.; Wang, S. Economic evaluation and development suggestion of distributed PV- Energy storage system in China. *Electr. Power* **2015**, *48*, 139–144.
25. Sun, B.; Liao, Q.Q.; Liu, Y.; Liu, Y.; Zhou, G.; Ge, H. Economic analysis of hybrid system containing distributed photovoltaic power and battery stored energy. *Electr. Power Constr.* **2016**, *37*, 102–107.
26. Wang, X.; Chu, C.; Cao, Z.; Chu, C.; Ju, M. Empirical analysis of cost-CO_2-energy benefits of distributed photovoltaic—Battery storage system—taking (PV-BSS) in a case study in rural Jiaozhou Shandong. *China Environ. Sci.* **2022**, *42*, 402–414.
27. Liu, J.; Cao, L.; Ma, J.; Zhang, J. Economic analysis of user's grid-connected PV system based on energy storage system. *Acta Energiae Solaris Sin.* **2012**, *33*, 1887–1892.
28. Gatto, A.; Sadik-Zada, E.R.; Lohoff, T.; Aldieri, L.; Vinci, C.P.; Peitz, K.A. An exemplary subsidization path for the green hydrogen economy uptake: Rollout policies in the United States and the European Union. *J. Clean. Prod.* **2024**, *440*, 140757. [CrossRef]
29. La Monaca, S.; Ryan, L. Solar PV where the sun doesn't shine: Estimating the economic impacts of support schemes for residential PV with detailed net demand profiling. *Energy Policy* **2017**, *108*, 731–741. [CrossRef]
30. Zhang, J.; Cho, H.; Luck, R.; Mago, P.J. Integrated photovoltaic and battery energy storage (PV-BES) systems: An analysis of existing financial incentive policies in the US. *Appl. Energy* **2018**, *212*, 895–908. [CrossRef]
31. Xiao, H.; Yue, C. The Comparison and Research on Supporting Policy of Renewable Energy Development of China and Britain[J/OL]. *Express Water Resour. Hydropower Inf.* **2024**, 1–7. Available online: http://kns.cnki.net/kcms/detail/42.1142.tv.20240307.1537.002.html (accessed on 23 April 2024).

32. Zhang, Y. Research on Economic Analysis and Investment Development Path of Despersed Wind Power Projects. Master's Thesis, North China Electric Power University, Beijing, China, 2020. [CrossRef]
33. Liu, Y.; Hao, M.; Li, G.; Yuan, S. Study on economic effect evaluation of wind power storage project: Levelized cost model and application analysis based on system dynamics. *Price Theory Pract.* **2021**, *11*, 96–101.
34. Wang, Q. *Advanced System Dynamics*; Tsinghua University Press: Beijing, China, 1995.
35. Tan, J.; Wang, B.; Li, Y. Application of system dynamics on comprehensive benefit valuation of demand response. *Autom. Electr. Power Syst.* **2014**, *38*, 128–134.
36. Dong, H.A.N.; Zheng, Y.A.N.; Yiqun, S.; Qiang, S.; Yibin, Z. Dynamic assessment method for smart grid based on system dynamics. *Autom. Electr. Power Syst.* **2012**, *36*, 16–21.
37. Zhao, X.; Feng, T.; Yang, Y. Impacting mechanism of renewable portfolio standard on China's power source structure and its effect. *Power Syst. Technol.* **2014**, *38*, 974–979.
38. Zhao, S.; Wang, B.; Li, Y.; Sun, M.; Zeng, W. System dynamics based analysis on incentive mechanism of distributed renewable energy. *Autom. Electr. Power Syst.* **2017**, *41*, 97–104.
39. Zhang, L.; Ge, L.; Chen, C.; Tang, M. Simulation on the development of residential distributed photovoltaic power genenation under the declining trend of Feed-in-Tariff. *J. Syst. Simul.* **2021**, *33*, 1397–1405. [CrossRef]
40. Xie, Y.; Bai, J.; Huang, Y.; Wang, S.; Wang, Y.; Hu, J. Analysis of annual power generation of bifacial PV array under occlusion of different spindle structures. *Acta Energiae Solaris Sin.* **2023**, *44*, 134–140.
41. Li, Y.; Wang, K. Research on the characteristics and economic analysis of new energy power generation. *Appl. Energy Technol.* **2022**, *6*, 51–53.
42. Zhang, Y. Study on the influencing factors of photovoltaic power generation efficiency. *Chin. Sci. Technol. J. Database (Dig. Ed.) Eng. Technol.* **2023**, *6*, 11–13.
43. Wang, Q.; Wang, S.; Liu, J.; Guo, W.; Kang, W.; Liu, D.; Hu, Y. Research on the phased Marketization scale and path of new energy in provincial power grids. *Glob. Energy Internet* **2023**, *6*, 406–416. [CrossRef]