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Economic and Social Benefits of Aquavoltaics: A Case Study from Jiangsu, China

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Abstract: Aquavoltaics is an innovative and beneficial solution that makes dual use of water area for photovoltaic (PV) power generation and aquaculture. Currently, China has made remarkable developments in aquavoltaics. This paper first analyzes the current development status of aquavoltaics in China, then takes the TW "fishery–PV integration" base project in Nanjing, Jiangsu Province, as a case study to analyze its economic and social benefits, and finally puts forward countermeasure suggestions for the development of aquavoltaics in China. It is found that Jiangsu Province is one of the clustering areas for the development of aquavoltaics in China, and the development of aquavoltaics in this province has a high level of specialization. The payback period (PP) of the TW "fishery–PV integration" base project is 10.44 years, the net present value (NPV) is USD 18.5334 million (the discount rate is 5%), and the internal rate of return (IRR) is 8.06%. The social benefits of this project are mainly reflected in the promotion of energy conservation and emission reduction, the alleviation of energy shortages, the optimization of land use, and the development of culture, tourism, science, and education. The development of aquavoltaics should be promoted by strengthening scientific research, paying attention to the impact of PV panel erection on the ecological environment of the waters, emphasizing the fishery farming part of the aquavoltaic project, and improving the commercial operation mode of the aquavoltaic project.

Keywords: aquavoltaics; economic benefits; social benefits; case study

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1. Introduction

In order to cope with climate change, countries around the world are developing renewable energy sources, thus realizing a low-carbon energy transition [1]. In this context, the application of photovoltaic (PV) systems is considered to have great potential [2,3], with efficiencies in light capture even exceeding those of photosynthesis [4]. The installation of PV systems in open areas minimizes the cost, which has led to the construction of some PV plants on agricultural land [5–7] and further led to the conflict between energy generation and food production [8–11]. Therefore, the development of agrivoltaics has become a solution [12–14]. Agrivoltaics, also known as "agriculture–PV integration", refers to both PV power generation and agricultural production on the same piece of land [15,16], realizing the dual-use of one piece of land [17], and emphasizing the mutual influence, competing relationship, and coupled symbiosis between PV power generation and agricultural production [18,19]. Aquavoltaics is a mode similar to agrivoltaics.

Aquavoltaics refers to the use of fishponds or mudflat wetlands to set up photovoltaic modules for power generation, forming a "power generation on the top, fish farming underneath" mode [20], which makes full use of the space, saves land resources, and regulates the aquaculture environment by using photovoltaic power plants [21]. China is the largest aquaculture country in the world, with a farming output of 52.242 million tons, accounting for 79.8% of the total national fishery production, providing about 1/3 of high-quality animal protein for urban and rural residents [22]. China's aquaculture mainly adopts pond, large water surface, mudflat, and rice paddy farming methods, with a farming area of more than 7.036 million hm^2 [23], which provides a good fishery resource base for the development of aquavoltaics. In addition, China's National Energy Administration issued the "Notice on Further Implementation of Relevant Policies on Distributed Photovoltaic Power Generation" in 2014, stating that "the use of land resources such as mudflats, fishponds, lakes, and other land resources to construct photovoltaic power generation projects" introduced aquavoltaic projects in the distributed PV project for the first time. Since then, China's aquavoltaics have entered a rapid development stage [24]. Currently, the installed capacity of aquavoltaic power plants in China is the largest in the world, and these projects are mainly distributed in the eastern coastal areas [20]. Therefore, it is important to analyze the economic and social benefits of aquavoltaics based on the Chinese case to promote its application in the world.

The existing research in the field of aquavoltaics covers engineering, environmental, economic, and social aspects, but the number of studies is relatively small. The overall situation is still in its infancy, and further research is needed. Especially in terms of case studies, there is a great lack of current research. Due to the rapid development of the photovoltaic industry [25,26] and abundant fishery resources [27], China has become the most successful country in the world in implementing the aquavoltaic mode, and its aquavoltaic projects have continuously improved their input–output efficiency [20]. In view of this, this paper first explored the current development status of aquavoltaics in China and then selected a project in Jiangsu to conduct a case study and analyze the economic and social benefits of the project. We hope to provide references for theoretical research and practical activities in the field of aquavoltaics.

The main contributions of this paper are as follows: (1) The development status and agglomeration of China's aquavoltaics are explored. (2) The economic and social benefits of the TW "fishery–PV integration" base project are analyzed. (3) Suggestions for the development of China's aquavoltaics are proposed.

The rest of this paper is organized as follows: The following section is a literature review. Section 3 analyzes the development status of aquavoltaics in China. In Section 4, materials and methods are presented. Section 5 summarizes and discusses the results. In Section 6, conclusions are drawn, and suggestions are put forward.

2. Literature Review

Goetzberger et al. have proposed the idea of coexistence between solar energy conversion and crop cultivation, whereas land used for solar energy conversion was previously considered unusable for other purposes. Coexistence in this context refers specifically to the modification of solar power installations so that the land can be used for crop cultivation at the same time [12]. This is carried out by raising the solar collectors 2 m above ground and increasing the spacing between them to avoid excessive shading of the crops. It is argued that these photovoltaic systems occupy only 1/3 of the land and light resources and that further improvements in technology can increase their applicability in crop production [12]. About 30 years later, Dupraz et al. combined these ideas and first proposed the concept of "agrivoltaic" [13]. Meanwhile, scholars have made optimistic predictions about the application of agrivoltaic systems. Harinarayana et al. believe that agrivoltaic systems can be successfully implemented in India and all over the world [28]. In Germany, people will be happy to accept it because the dual utilization of land will not reduce the area of crop cultivation [29]. In the Phoenix Metropolitan Statistical Area (MSA) of the United States, the implementation of the above idea can meet the social demand for clean electricity while at the same time serving to protect the surrounding land for agricultural production, and therefore, the introduction of such a project can be considered for the area [17]. Dinesh et al. developed a coupled model of photovoltaic power generation and agricultural production to assess the technical potential of agrivoltaics. The results showed that by simply converting American lettuce cultivation to agrivoltaic mode, the PV generation capacity could be increased by 40–70 GW, indicating that agrivoltaic systems have great potential for application [14]. In China, the coupling coordination degree of agriculture and PV industry is mainly fluctuating and rising [30]. As a "PV+" mode [31], China's PV agriculture has entered the stage of niche integration [32]. By the end of 2020, the installed capacity of grid-connected photovoltaic agriculture projects in China accounts for about 7% of the total installed photovoltaic power capacity [33]. Among them, many projects are modeled as aquavoltaics [34].

Pringle et al. stated that floating photovoltaic (FV) systems, once combined with fish farming, can form an agrivoltaic-like system, which they termed an "aquavoltaic system" [21]. This type of installation is called floating PV by using appropriate technology to float the PV panels on the water body [35]. The world's first floating PV plant was installed in 2007 in Aichi, Japan, with an installed capacity of only 20 kW, and many countries, including China, have since joined in the construction of floating PV plants. Bai et al. predicted the potential installed capacity of floating PV in China range from 705.2 GW to 862.6 GW, with a corresponding annual power generation of 1164.9 TWh to 1423.8 TWh [36]. As a matter of fact, agrivoltaics is a larger concept that is not limited to the combination of floating photovoltaics and fish farming. According to Zhao et al., aquavoltaics is to set up photovoltaic panels on the aquaculture water surface so as to form the innovative mode of "power generation on the top and fish farming on the bottom". It is a perfect combination of emerging industries and modern agriculture, coupled with the development of recreational agriculture, which can form the superimposition of primary, secondary, and tertiary industries and fully improve the land utilization efficiency [37]. Since the PV modules in the aquavoltaic mode are located in an aquatic environment, which is different from the environment in which modes such as terrestrial PV and rooftop PV are located, some scholars have researched the relevant influencing factors of the power generation performance of aquavoltaic power plants, such as the placement method [38], solar radiation [39], and so on. Due to the more limitations in the installation of photovoltaic panels in aquavoltaic power stations compared to traditional ground-based photovoltaic power stations. For example, the installation height, the moisture resistance issues, and so on. All of these will increase the construction cost of the fishery photovoltaic complementary power station. Therefore, if we only consider the single aspect of PV power generation, the levelized cost of energy (LCOE) of aquavoltaic power generation is higher than that of terrestrial PV [21]. However, aquavoltaics also includes the aquaculture part, especially the aquaculture of some high-value-added shade-loving fish, which can greatly improve the economic benefits of the project [40]. Aquavoltaics also has good environmental benefits, such as reducing algal growth under eutrophication [41], generating clean electricity with no CO_2 emissions, and saving water resources by preventing evaporation. It also saves valuable land for agriculture, mining, tourism, and other activities by reducing the amount of water used to clean PV modules due to the installation of PV panels on water bodies [42]. However, the economic and environmental synergies of aquavoltaics are not optimal and need to continue to be optimized. In addition, it reduces bird collisions with the panels compared to ground-mounted PV systems [43] and improves water quality in reservoirs [44]. Its social benefits are similar to the coupled model of agricultural cultivation and PV power generation, including energy saving and environmental protection, accelerating energy and power restructuring, driving employment, and promoting economic development.

In summary, aquavoltaics is a mode similar to agrivoltaics. It is a mode that photovoltaic panels are erected above the water surface while the fishery is being cultivated in the water and is not limited to the combination of floating photovoltaics and fishery aquaculture. In this way, whether photovoltaic power generation and fishery aquaculture can be "symbiotic" has become the key to realizing the economic, environmental, and social benefits of aquavoltaics. Currently, there is a lack of research on aquavoltaics [45], especially on its various benefits. China's aquavoltaics is an important part of photovoltaic agriculture, and it carries out numerous project practices throughout the country [46].

This paper selected an aquavoltaic project in Jiangsu province as a case and analyzed its economic and social benefits, which have implications for research and practice in the field.

3. Development Status of Aquavoltaics in China

This part first discusses the development overview of aquavoltaics in China and then applies the concentration ration index and location quotient to analyze its agglomeration.

3.1. Overview of the Development of Aquavoltaics in China

The sample data used to analyze the development profile of aquavoltaics in China were collected from the China Energy Storage Network (CESN, www.escn.com.cn, accessed on 18 June 2024), which has a special section to disclose the status of agricultural PV projects that have been filed, tendered, awarded, contracted, commenced, completed, accepted, and connected to the grid. As of 31 December 2023, a total of 10,975 pieces of information about agricultural PV projects have been disclosed on CESN. For this information, firstly, the duplicated disclosure information was eliminated, and then considering the possible uncertainty of the projects, the projects that are still in the process of filing, bidding, winning, contracting, starting, completing, and accepting were eliminated. Finally, 154 aquavoltaic projects that have been connected to the grid and generated electricity were sorted out, and the number of additional projects in each year and the installed capacity are shown in Table 1.

Table 1. Number and installed capacity of additional aquavoltaic projects in China from 2011 to 2023.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	Total
Number of additional projects	1	0	5	5	11	26	42	11	2	12	7	14	18	154
Installed capacity of additional projects (MW)	20	0	179.8	300	431.25	1198	2330.5	649	360	1938	1298.43	1737.6	3275.26	13,717.84
Average installed capacity of additional projects (MW)	20	—	35.96	60	39.20	46.08	55.49	59	180	161.5	185.49	124.11	181.96	89.08

As can be seen from the number of additional projects in Table 1, China's aquavoltaics started in 2011–2014 and began to enter a period of rapid development in 2015. This is mainly because China's National Energy Administration issued a document on the development of aquavoltaics in September 2014. Then, in 2018, China's aquavoltaics entered a stable development stage. It should be noted that, in China, major events related to the national economy and people's livelihood, such as the development of the new energy industry, will formulate five-year plans. The period from 2016 to 2020 is the 13th Five Year Plan period, and the period from 2021 to 2025 is the 14th Five Year Plan period. Generally, industrial development will be more rapid in the early to mid-stages of the five-year plan. According to the data of installed capacity of additional projects in the table, it can be seen that the installed capacity of aquavoltaic projects in China is fluctuating and rising, with the first rising stage before 2017, a decline in 2018–2020, especially a significant decline in 2018–2019, and the second rising stage from 2021 to the present. According to the data of the average installed capacity of additional projects, they basically show a gradual upward trend, growing from 20 MW in 2011 to 181.96 MW in 2023, and the average installed capacity of additional aquavoltaic projects during the whole period is 89.08 MW.

3.2. Agglomeration Analysis of Aquavoltaics

3.2.1. Concentration Ration Index

Among the indicators of industry agglomeration analysis, the concentration ration index is the most commonly used, which indicates the share of the output value of the top regions in the industry scale ranking in the total output value [47]. Using the above data on the installed capacity of aquavoltaic power plants in each region, the concentration ration index of aquavoltaics can be calculated. The calculation formula is as follows:

$$CR_n = \sum_{i=1}^{n} S_i \quad (1)$$

In Equation (1), CR_n indicates the sum of the proportion of the total installed capacity in the first n regions (in this study, it refers to various provinces in China) with the largest scale, and S_i indicates the share of installed capacity of aquavoltaic projects in the region i in the total installed capacity of this type of project. In addition, n in the formula generally takes the value of 1, 4, 8, and so on [47]. Concentration ration index can figuratively reflect the agglomeration level of aquavoltaics, and the larger the value of CR_n is, the more concentrated the industry is.

It should be noted that, considering the availability of data, the installed capacity of the aquavoltaic power plant is used here to replace the production value. The output value of aquavoltaic projects is mainly divided into two parts: the output value of photovoltaic power generation and the output value of fisheries. Generally, the former accounts for a larger proportion, and the former is directly related to the installed capacity of the power plant. In addition, the influencing factors of fishery production value are production and price, and production is mainly affected by the area of the aquaculture area. While the installed capacity of the aquavoltaic power plant is directly proportional to the area of the aquaculture area. Summarizing the above two points, it is reasonable to use the installed capacity of an aquavoltaic project to replace its output value. Hence, based on the installed capacity data of aquavoltaic projects in Table 1, the concentration ration index of aquavoltaics was calculated by applying Equation (1), as shown in Table 2.

Table 2. Concentration ration index of aquavoltaics in China from 2011 to 2023.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
CR_1	1	1	1	0.92	0.687	0.408	0.241	0.293	0.273	0.202	0.2171	0.1935	0.1473
CR_4	1	1	1	1	0.946	0.892	0.735	0.740	0.738	0.616	0.624	0.571	0.523
CR_8	1	1	1	1	1	1	0.935	0.933	0.938	0.870	0.852	0.838	0.832

According to the value of CR_1 in Table 2, it can be seen that in 2011–2013, the aquavoltaic projects in China were concentrated in only one region, which was Jiangsu Province. Starting in 2014, other regions in China have completed the grid-connected power generation of aquavoltaic projects one after another, and the earlier ones are Anhui and Hubei. However, according to the value of CR_4, it can be seen that after 2015, there are more than four regions in China that put aquavoltaic projects into operation. The value of CR_8 shows that after 2017, there are more than eight regions in China with aquavoltaic power plants connected to the grid, thus entering a period of comprehensive development. Meanwhile, the decreasing trend of CR_8 is relatively gentle compared with CR_1 and CR_4, and the value stays above 0.8, which indicates that the aquavoltaic projects are mainly concentrated in certain regions, reflecting a strong geographical nature. According to the results obtained from the 2023 data, the top four provinces in terms of total installed capacity are Jiangsu, Zhejiang, Anhui, and Hubei, and the common characteristic of these regions is rich fishery resources, among which Jiangsu has the highest fishery output value.

3.2.2. Location Quotient

Location quotients can be used to measure the level of specialization of an industry in a specific region and can reflect the position and role of the region in the higher-level region with regard to the relevant industry [48]. For the measurement of regional industrial agglomeration, this index has a better measuring effect. The formula is as follows:

$$LQ_{ij} = \frac{e_{ij}/e_i}{e_j/e} \quad (2)$$

According to the research content of this paper, LQ_{ij} in Equation (2) denotes the location quotient of agricultural PV projects of category j in the region i, and e_{ij} denotes the installed capacity of agricultural PV projects of category j in the region i. $e_i = \sum_j e_{ij}$ denotes the installed capacity of all the agricultural PV projects in the region i, and $e_j = \sum_i e_{ij}$ denotes the total installed capacity of agricultural PV projects of category j in all the regions. $e = \sum_j \sum_i e_{ij}$ denotes the total installed capacity of agricultural PV projects in all the regions. $LQ_{ij} > 1$ represents that the installed capacity of a certain type of agricultural PV project in a certain region is higher than the proportion of the installed capacity of that type of agricultural PV project in the region than the proportion of the installed capacity of that type of agricultural PV project in all regions. $LQ_{ij} = 1$ and $LQ_{ij} < 1$ represent the average level of specialization and a disadvantageous state, respectively.

Here, we only measure the location quotient of the four provinces with the highest installed capacity of the aquavoltaic power plants mentioned above. Because the main development of aquavoltaics in China is mainly after the government released the relevant documents in September 2014, this article sets the period of location quotient measurement as 2015–2023, and the results of the calculation are shown in Table 3.

Table 3. Location quotient of aquavoltaics in Jiangsu, Zhejiang, Anhui, and Hubei from 2015 to 2023.

Year		**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Location quotient	Jiangsu	2.797	2.600	2.247	2.259	2.315	2.094	2.094	2.094	2.128
	Zhejiang	1.445	1.307	1.486	1.452	1.488	1.488	1.664	1.681	1.589
	Anhui	0.364	0.929	1.419	1.455	1.670	1.510	1.550	1.586	1.718
	Hubei	2.064	1.268	1.184	1.1569	0.619	0.877	0.673	1.463	1.592

As can be seen from Table 3, during the period of 2015–2023, the value of location quotient of aquavoltaics in Jiangsu is the highest among the four provinces with the best development of aquavoltaics. Although it has declined in recent years, it still remains above 2, indicating that the development of aquavoltaics in this province has always had a high level of specialization. Therefore, a certain aquavoltaic project in Nanjing, Jiangsu Province, is selected as a case study in the following.

4. Materials and Methods

4.1. Site Slection

Nanjing is located in the eastern part of China and the central part of the lower reaches of the Yangtze River. It is the capital city of Jiangsu Province. As shown in Figure 1, the place marked with a red dot on the map is Nanjing City. It is one of the 13 prefecture-level cities in Jiangsu Province and is located in the southwestern part of Jiangsu (see Figure 1). The geographical coordinates are between 31°14′ and 32°37′ north latitude and 118°22′ and 119°14′ east longitude, and the average solar irradiation is 13,316 kWh/m^2/a. It has a total area of 6587.04 km^2 and a total population of 9.547 million. The water area of Nanjing reaches more than 11%, and the total length of the shoreline along the river is 200 km. There are a total of 120 large and small rivers in Nanjing, with abundant fishery resources. At present, there are five large-scale aquavoltaic projects in Nanjing, four of which are still under construction and one of which has been connected to the grid to generate electricity. In this paper, we select the aquavoltaic project that has already been connected to the grid to generate electricity—Jiangsu Nanjing Liuhe Longpao TW “fishery–PV integration” base (the red mark in Figure 2).

Figure 1. Administrative divisions of Jiangsu Province.

Figure 2. Map of the study site.

4.2. Data Collection and Organization

Firstly, the research team visited the location of the case project in November–December 2019 to obtain a preliminary understanding of the basic situation of the project.

Second, we collected data and information on the location, grid-connected power generation time, land area, and power plant size of the case project through CESN before this research (see Table 4). Subsequently, the research team visited the project location in July–August 2024 and conducted in-depth interviews with relevant personnel involved in the operation and maintenance of the project and local farmers conducting farming operations to collect data on the project's investment, cost, and revenue (see Table 5).

Table 4. Basic information of the TW "fishery–PV integration" base project.

Basic Information Items	Specific Information
Site	Longpao Street, Luhe District, Nanjing City, Jiangsu Province, China
Start time of operation	June 2018
Total area	146.67 ha
Water surface area	100 ha
Area covered by photovoltaic panels	60 ha
Types of aquatic products	lobsters and hairy crabs
Annual aquatic production	15 tons
Installed capacity	50 MW
Annual power generation	51 million kWh
Project period	25 years
Total power generation over the project period	1.275 billion kWh

Table 5. Investment, costs, and revenues of the TW "fishery–PV integration" base project.

Related Items of Investment, Costs and Revenues	Specific Information
Total investment	USD 55.9131 million
PV investment	USD 49.8685 million
Fishery investment	USD 6.0447 million
O&M costs of photovoltaic power generation	USD 0.0060/W, 15.5% of CAPEX
Operational costs of fisheries	USD 1.7711 million per year
Feed-in tariff	USD 0.1051/W
Fishery income	3.6270 million per year
PV total income	USD 121.8955 million
Fisheries total income	USD 46.3928 million
Total income	US 168.2883 million
Income tax rate	25%

4.3. Methods

In this paper, two types of methods, qualitative and quantitative, were combined to analyze the economic and social benefits of the case projects. Among them, qualitative methods were used to analyze the social benefits of the case while quantitative methods were used to analyze the economic benefits of the case. The quantitative methods used in the article are as follows:

4.3.1. Payback Period (PP)

The payback period (PP) was used to measure the investment recovery of the case project. PP refers to the period during which the project needs to recover the initial investment, which is expressed in the calculation as the time when the cumulative net cash flow of the project is 0. It is an auxiliary indicator used for the preliminary evaluation of the project's economy and generally does not take the time value of money into account. Hence, PP is defined as [49]:

$$0 = \sum_{t=0}^{PP} C_t \quad (3)$$

where C_t represents the net cash flow of the project in year t.

4.3.2. Net Present Value (NPV)

The net present value (NPV) was used to measure the profitability of the case project over the entire project period. NPV is the present value of the annual net cash flow over the entire project period. A positive NPV means that the project is economically viable. The higher the NPV, the better the economic viability of the project. The formula for calculating NPV is as follows [50]:

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \quad (4)$$

where C_t denotes the net cash flow of the project in year t; i is the discount rate; and n is the project period.

4.3.3. Internal Rate of Return (IRR)

We measured the real rate of return of the case project throughout the project period by using the internal rate of return (IRR), which is the discount rate when the present value of the net cash flow of the project period is 0. The IRR greater than the required rate of return indicates that the project is economically feasible. The higher the IRR, the better the project's economics. Hence, IRR is defined as [51]:

$$0 = \sum_{t=0}^{n} \frac{C_t}{(1+IRR)^t} \quad (5)$$

where C_t denotes the net cash flow of the project in year t and n is the project period.

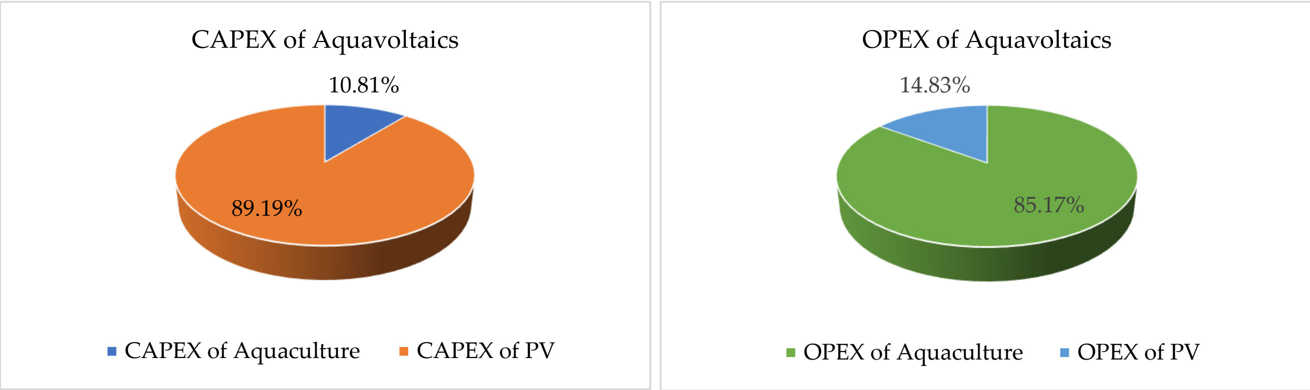
5. Results and Discussion

5.1. Project Overview

The TW "fishery–PV integration" base project was contracted and constructed by TW Group. This project is located in Longpao Street, Liuhe District, Nanjing City, Jiangsu Province, China, covering an area of about 146.67 ha, of which the standardized ponds are about 100 ha (see Figure 3). These ponds mainly culture lobsters and hairy crabs, which are shade-loving aquatic products, with an annual fish production of 150 tons. The total installed capacity of the project reaches 50 MW, and the annual power generation is 51 million kWh. The equipment life is 25 years, and the total power generation is 1.275 billion kWh. The area of the pond covered by PV panels is about 60 ha, accounting for about 60% of the standardized fishing ponds, and there is no impact on the normal maintenance of the fishing ponds. The basic information of the above case projects is shown in Table 4.

Figure 3. Overall layout of the TW "fishery–PV integration" base project.

The total investment of this aquavoltaic project is USD 55.9131 million (the exchange rate is 6.61741), of which USD 49.8685 million is invested in photovoltaic, which is divided into two parts: USD 49.6418 million of investment in fixed assets and USD 0.2267 million of liquidity investment. The remaining USD 6.0447 million is invested in fishery, which is divided into USD 5.4402 million of investment in fixed assets and USD 0.6045 million of liquidity investment. The cost structures of aquavoltaics are shown in Figure 4. All the above sources of funding are our own funds. The project generates 51 million kWh of electricity per year, with a feed-in tariff of USD 0.1051, a fishery income of USD 3.6270 million, and a fishery cost of USD 2.1156 million.



(**a**) (**b**)

Figure 4. Cost structures of aquavoltaics.

5.2. Economic Benefit Analysis

Before calculating the related indicators of economic benefit analysis, we first have to estimate the cash flow of the case project. Based on the data in Table 5 and some of the data in Table 4, this article made a detailed estimation of the annual cash flow of the project, and the results are shown in Table 6. It should be noted that the whole project period is 26 years because there is a 1-year construction period. Considering the attenuation of PV module power generation, we set the total attenuation ratio of solar modules for 25 years to 2% and use linear interpolation to estimate the annual power generation of the project. In addition, although the life of the project is 15 years, this paper sets the depreciation life of the fixed assets to 15 years and the salvage value rate to 5% in light of the actual situation. Finally, it should be noted that the following calculations are based on the normal and continuous operation of the project without considering factors such as machine failures, human damage, and natural disasters.

As shown in Table 6, due to the attenuation of the PV modules, the annual net cash flow gradually decreases from year to year. The highest cash flow occurs in the final year because of the recovery of salvage value of fixed assets and liquidity in that year. The cumulative net cash flow of the project turns from negative to positive at the 11th year, indicating that the breakeven time of the project is between 10 and 11 years. Without considering the time value of money, the net cash flow for the entire project period is USD 81.3034 million.

Based on the data of net cash flow in Table 6, the payback period of the project was calculated by applying Equation (3), and the result indicates that it will take 10.44 years to recover the total investment of the project without considering the time value of money. Setting the discount rate at 5% (base rate of return), the NPV of the project was calculated by applying Equation (4), and the result is USD 18.5334 million, indicating that the project is economically feasible in the lifetime of 26 years. The internal rate of return was calculated by applying Equation (5); the result is 8.06%, indicating a true rate of return of 8.06% for the project.

Table 6. Cash flows of the TW "fishery–PV integration" base project.

Time (Year)	Fixed-Asset Investment (USD Million)	Liquidity Investment (USD Million)	Annual Net Cash Flow (USD Million)	Cumulative Net Cash Flow (USD Million)
0	55.0820		−55.0820	−55.0820
1		0.8311	−0.8311	−55.9131
2			6.0574	−49.8557
3			6.0252	−43.8305
4			5.9933	−37.8372
5			5.9617	−31.8756
6			5.9303	−25.9453
7			5.8991	−20.0462
8			5.8682	−14.1779
9			5.8376	−8.3404
10			5.8072	−2.5332
11			5.7770	3.2438
12			5.7471	8.9909
13			5.7174	14.7083
14			5.6880	20.3963
15			5.6588	26.0551
16			5.6298	31.6849
17			4.7289	36.4138
18			4.7004	41.1142
19			4.6721	45.7864
20			4.6441	50.4304
21			4.6162	55.0467
22			4.5886	59.6353
23			4.5613	64.1966
24			4.5341	68.7307
25			4.5071	73.2378
26			8.0656	81.3034
Total	55.0820	0.8311	81.3034	

In addition, due to the possibility of subsidy policy rollback and fluctuations in fishery income, we conducted further multi-scenario analysis. Specifically, we analyzed the economic benefits of the project under scenarios of a 5%, 10%, and 20% reduction in electricity prices and fishery revenue. The results are shown in Table 7.

Table 7. Economic benefits in different scenarios.

Decline Rate of Feed-In Tariff	PP (Year)	NPV (USD Million)	IRR	Decline Rate of Fishery Income	PP (Year)	NPV (USD Million)	IRR
5%	10.77	16.1494	7.69%	5%	10.67	16.7948	7.79%
10%	11.12	13.7653	7.32%	10%	10.90	15.0561	7.52%
20%	11.90	8.9972	6.54%	20%	11.42	11.5789	6.97%

According to Table 7, the economic benefits of the TW "fishery–PV integration" base project have a certain degree of robustness. Even if electricity prices or fishing revenue decrease by 20%, it is still economically feasible. In addition, compared to fishery income, the economic benefits of this project are more sensitive to changes in feed-in tariff.

5.3. Social Benefit Analysis

5.3.1. Promoting Energy Conservation and Emission Reduction

PV power generation has a good emission reduction effect. According to the latest published coal consumption standards for thermal power generation in China, for every 1 kWh of electricity generated by thermal power, 0.3 kg of standard coal, 0.004 m^3 of water, 0.831 t/a of carbon dioxide, 0.025 t/a of sulfur dioxide, and 0.227 t/a of dust are needed [52], with the corresponding consumption and emission of relevant raw materials and waste gases. With a life cycle of 25 years, the power generation of the TW "fishery–PV integration" base project is expected to generate a total of 1.275 billion kWh, reducing the use of standard coal to 38.25 tons, water to 510 m^3, and the emission of carbon dioxide to 105,952.5 tons, sulfur dioxide to 3187.5 tons, and dust to 28,942.5 tons.

5.3.2. Alleviating Energy Shortage

In today's rapid economic development, the problem of energy shortage is becoming more and more prominent. Energy supply and demand may appear in three scenarios: supply and demand are basically balanced, with a zero gap; supply is greater than demand, with a demand gap; supply is less than demand, with a supply gap. At present, although there is still a small amount of fossil fuels to be imported, China's energy supply and demand are basically balanced, which is the result of the vigorous development of renewable energy. According to data released by the National Energy Administration for the first half of 2024, the combined installed capacity of wind power and PV power generation has exceeded that of coal power, with 467 million kW of wind power and 714 million kW of PV power, and PV power generation has greatly alleviated China's past energy shortages [53]. The energy supply and demand situation of each province in China varies from place to place. In Jiangsu Province, for example, the annual electricity generation in 2022 is about 594.898 billion kWh, and the electricity consumption is about 739.955 billion kWh, which means that there is a shortfall of about 145 billion kWh in the electricity demand in Jiangsu Province in 2022. In this case, Jiangsu combines its own resource advantages and vigorously develops aquavoltaics, which can alleviate this problem to a certain extent.

5.3.3. Optimizing Land Use

As a large province of PV industry, Jiangsu Province has a complete chain of all kinds of products in the upstream, midstream, and downstream of PV industry, but the shortage of land resources makes it difficult for PV power generation projects to be reasonably distributed in this province. The emergence of aquavoltaic mode alleviates the above problems. Taking TW "fishery–PV integration" as an example, it occupies an area of about 146.67 hm^2, and without affecting the fishery farming, the coverage rate of PV panels is about 45%. According to the standard of generating 51 million kWh per year, if the aforementioned 145 billion kWh of power shortfall in Jiangsu Province is to be met by aquavoltaic mode, 419.5 thousand hm^2 of land will be needed. While the target fishery farming area in Jiangsu Province's "14th Five-Year Plan" for fishery development is 1350 thousand ha. Therefore, utilizing about 30% of the fishery ponds in Jiangsu Province without affecting fishery farming can ensure the green energy transformation of Jiangsu Province. At the same time, aquavoltaics promotes the integrated aquaculture of fisheries, which is conducive to the scientific aquaculture of fisheries.

5.3.4. Developing Culture, Tourism, Science, and Education

Combining the local culture of "Longpao soup dumplings", the TW "fishery–PV integration" base project promotes its own high-quality Chinese mitten crabs to local cultural activities with the theme of "crab roe soup dumplings" at the annual Crab Roe Soup Dumpling Festival. The project uses large-scale aquavoltaic facilities and related modern aquaculture equipment to attract tourists to visit the tourism so as to drive the local culture and tourism industry. In addition, as a provincial demonstration base, the TW "fishery–PV integration" base project rationally plans and builds science and education bases according to geographical advantages and carries out science popularization activities on the ground so as to improve the scientific and technological quality of the whole population. Meanwhile, the project plays the role of scientific and technological innovation and supports and leads the green development of aquavoltaics.

5.4. Discussion

The results of the economic benefit analysis showed that the PP of the TW "fishery–PV integration" base project is 10.44 years, a value close to that of Zhu et al. (10.5 years) [54], but different from that of Gan [55] and Jing et al. [56], which are 12.4 years and 9.5–10.1 years, respectively. The reason is that the objects of the latter two studies are different from this paper; one is a case study of an aquavoltaic project in Guangxi, and the other is a study of the overall aquavoltaic situation in China. Comparing the results of Jing et al., the PP of the case project did not reach the average level in China for the following three reasons. First, from the temporal dimension, the input–output efficiency of Chinese fishery–photovoltaic projects grows slowly until 2018 and starts to improve significantly only after 2018, which is when the case project was connected to the grid and generated electricity. Secondly, from the spatial dimension, although Jiangsu is one of the best developing regions of China's aquavoltaics, its input–output efficiency is at the bottom of these regions, which obviously also involves the factor of time. Because Jiangsu has the earliest development of aquavoltaics, its installed capacity accounted for 30% of the total installed capacity of the national aquavoltaic power plant in 2018, but the technical efficiency of PV modules was low at that time. Therefore, from a technical point of view, the input–output efficiency of the regions in China with the earliest development of aquavoltaics is not the highest. In addition, this paper considers the attenuation phenomenon of solar modules when estimating cash flow, but many studies do not consider this factor. Since NPV is an absolute measure, it is not reasonable to simply compare the results of different studies. In the case of a discount rate of 5%, the NPV of the project is positive, while if the discount rate is set to 10%, the NPV turns negative, which is consistent with the findings of Chen et al. [57]. It can be seen that the discount rate is a very important factor for the calculation of NPV and a very sensitive factor to the results of NPV calculation, which needs to be taken into account when calculating NPV. The IRR of this case project is 8.06%, which is slightly lower than the findings of Chen et al. (8.35–10.22%), which is still due to the above factors of time and space discussed when analyzing the PP's failure to reach the average level in China. As for the results of the analysis of social benefits, the first three points are common to the aquavoltaics, and we have analyzed them specifically in the context of the project itself, Jiangsu Province, and the actual situation in China. The fourth of the social benefits is unique to this project, which makes good use of the local characteristic cultural industry and its title of provincial demonstration base for cultural, tourism, science, and education activities, which is a good reference for other aquavoltaic projects.

6. Conclusions and Suggestions

This paper first explored the current development status of aquavoltaics in China. Then, it selected the TW "fishery–PV integration" base project in Nanjing, Jiangsu Province, as a case and analyzed its economic and social benefits. Finally, we draw the following conclusions: (1) The development of aquavoltaics has a strong territoriality. Jiangsu is one of the better-developed regions of aquavoltaics in China, and its aquavoltaics industry has a very high level of specialization. (2) The PP of the TW "fishery–PV integration" base project is 10.44 years, the NPV is USD 18.5334 million (the discount rate is 5%), and the IRR is 8.06%, which means good economic benefits. However, due to the early time of completion, there is a technical efficiency gap between this project and the projects that have been put into operation in recent years, and this gap will be reacted to the economic benefits. (3) The TW "fishery–PV integration" base project has social benefits such as promoting energy conservation and emission reduction, alleviating energy shortages, optimizing land use, etc. Moreover, the project combines local characteristic industries to promote the development of the cultural tourism industry and makes use of its provincial demonstration base title to carry out science and technology popularization activities, which are of good promotion value.

According to the analysis of this article and combined with the above conclusions, the following suggestions are given for the development of aquavoltaics: (1) Strengthen scientific research. Aquavoltaics is an important part of agricultural photovoltaics, and it has become the most important part of agricultural photovoltaics in some countries, such as China. However, too little research has been conducted on aquavoltaics [58]. After searching, we found that as of 25 August 2024, there are only eight articles with the title aquavoltaic or aquavoltaics on the Science Direct website. (2) In particular, the focus should be on the impact of the erection of photovoltaic panels on the ecological environment of the waters. Scholars have conducted in-depth research on this issue. Overall, the construction of aquavoltaic power stations will have an impact on water quality and aquatic organisms, but it is not significant [41,59]. However, the coverage area of photovoltaic panels cannot be too high. When it exceeds 75%, the amounts of plankton in the water will decrease to the lowest level [60]. Due to the current research observation period not being long enough, the ecological impacts of the operation of aquavoltaic projects should be studied in the longer term and in greater depth. The installation ratio of photovoltaic panels should be reasonably set to prevent excessive impact on the growth of plankton. (3) Emphasis should be placed on the fishery farming component of the aquavoltaic project to enhance the synergistic effect of PV power generation and fishery farming. In the process of estimating the annual cash flow of the TW “fishery–PV integration” base project, we found that fishery farming provides about 25% of the project’s revenue, and without this part of the revenue, it is likely that the project is not economically feasible. However, in actual application, the problem of “emphasizing PV over fishery” occurs from time to time, and in December 2023, China’s Ministry of Agriculture and Rural Development (MARD) demanded a deadline for rectification of such problems in existing aquavoltaic projects. The above problems are essentially the failure to deal with the relationship between fishery farming and PV power generation, leading to the eventual trivialization or even abandonment of fishery farming. However, this does not ensure the agricultural nature of the land in the first place, and in addition, it has a great impact on the economic benefits of the project. Therefore, the synergistic effect of fishery farming and photovoltaic power generation should be utilized without affecting fishery farming. (4) Improve the business mode of the operation of the aquavoltaic projects. Drawing on the case study project in this paper, the aquavoltaic project can be extended to “creative fishery”, with photovoltaic scientific and technological fishery display as the theme, introducing science popularization, sightseeing, tourism, leisure, and other elements, setting up a sightseeing experience area, combining the aquavoltaic project and tourism, and realizing the expansion of the business mode. At the same time, it can also play the role of popularizing science and increasing the public’s understanding of agricultural photovoltaics. In addition, aquavoltaics can also be combined with local advantageous industries to enhance their economic value. In this way, the aquavoltaic project can reflect higher economic and social benefits.

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