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A techno-economic comparison between grounding PV and floating PV for shore power generation: Case study of Yangshan port

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ABSTRACT

Electrification is taking place to reduce the emissions from maritime transportation by substituting ships' auxiliary engine generation with shore power systems, therefore the power demand at berths increases dramatically. In this paper, we take Yangshan Port as an example to evaluates the feasibility of different photovoltaics (PV) technologies to suffice shore power demand based on geographic information system. The results show the potential shore power demand at Yangshan port is 288.8 MW, which can be sufficed by deploying PV either on available land or on water area. The further techno-economic comparison between conventional grounding PV and floating PV reveals that although the system cost of floating PV is higher than grounding PV, the higher efficiency of floating PV due to the cooling effect of water, in turn, results in a lower levelized cost of electricity (LCOE). The LCOE of all types of PV system is much lower than the retail electricity rate at Yangshan Port, which indicates that with the assistance of PV technology, high cost, the biggest hindrance of prompting shore power at Yangshan port can be overcome, and integrating PV technology at ports is a promising and practical solution to cope with electrification trend in the maritime transportation sector.

Keywords: PV integration, grounding PV, floating PV, port, techno-economic analysis.

NOMENCLATURE

Abbreviations	
CNY	Chinese yuan
LCOE	Levelized cost of electricity
NOCT	Nominal operating cell temperature
PV	Photovoltaics
ROI	Return on investment
Symbols	
A_c	Array area
A_{pv}	Module area
G_t	Global incident solar radiation
P_i	The i_{th} hour power output of PV array
P_{pv}	Array power
T_a	Ambient temperature
T_{STC}	STC temperature
$\eta_{inverter}$	Efficiency of the inverter
η_{PV}	Efficiency of the array
$\eta_{PV,STC}$	STC efficiency of the array
μ	Temperature coefficient of the array
ν	Actual wind speed

1. INTRODUCTION

As an important infrastructure for maritime transportation, ports connect lands and ocean, which are vital to transportation, trading, and economy.[1; 2] However, there are also emission issues around it. When

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calling at ports, ships use auxiliary power generators to generate electricity, which inevitably emits air pollutants,[3-5] which has adverse effects on the environment, air quality, and human health.[6-8] According to Fu's work, in 2013, 86.3 ± 0.3 Tg CO_2 was emitted from shipping activity in China.[9] Substituting auxiliary power generators by shore power while ships are calling at ports is an effective method to tackle the emission problem at ports.[10; 11] To reduce pollutant emissions and promote the sustainable development of

Fig. 1. The bird's-eye view of Yangshan Port.

the marine industry, the Chinese government has launched a series of policies such as the "Notice on the Implementation Plan for the Prevention and Control of Pollution from Ships and Ports (2015-2020)" and the "Port Shore Power Layout Plan", which set the target, by 2020, more than 50% of the berths in major ports and the emission control area will have the ability to supply shore power to ships.[12; 13] As of the end of 2019, more than 5,400 shore power facilities have been built across the country, covering more than 7,000 berths, achieving 81% of the target.[14] Although the deployment of shore power is very rapid, there are still problems at this stage.[15] First of all, the shore power system supplies electricity to ships from the local electricity grid, which guarantees zero emissions on ports, however, china's power sector is coal-dominated, the emissions brought by the plant-side still have the potential to be avoided. Secondly, some ports in China are far away from the land, so the cost of power grid expansion is high due to construction difficulties. Lastly, the current high price of shore power in China has inhibited ships' desire to use it. Therefore, using on-site technology to deploy power generation facilities in ports is a more suitble solution.[16; 17] Many ports, which have large open space and wide water area with few construction restrictions, and are ideal places for PV installations. Therefore, we take the Yangshan deep-water port in Zhejiang, China as a case to study the possibility and economic performance of deploying PV on-site to meet shore power demand, and compare the differences between various PV technologies.

2. THE DESCRIPTION OF THE YANGSHAN PORT

Yangshan Deep-water Port is located on Xiaoyangshan Island in the Zhoushan archipelago, 32 kilometers away from Luchao Port in Nanhui District, Shanghai. It is a natural harbor with a water depth of 15 meters. At present, the Yangshan Port has 23 berths in total, and the largest berth can accommodate 150,000-tonnage cargo ships. At present, the port shore power system has been connected to the power grid for operation.

3. METHODOLOGY

3.1 Geographical Information Collection

The geographic information, satellite images, and available area of Yangshan Port are all obtained through the geographic information system GOOGLE Earth Pro.[18]

3.2 Power demand estimation

We first collected the specifications of berths at Yangshan Port, and estimated the maximum energy demand of each berth based on its capacity, according to the reference value in the Chinese national standard JTS 155-2012.[19]

3.3 Climate data collection

Global horizontal radiation, diffuse horizontal radiation, ambient temperature and wind speed data are all gathered from the Meteonorm Global climate database.[20]

3.4 PV system simulation

3.4.1. Input data for the simulation model

The input data for the PV system simulation are summarized in Table 1.

Table 1. Input data for PV generation simulation

Parameter	Value
Latitude	30.6
Standard meridian	130
Local meridian	122.1
Ground reflectance	0.4
$\eta_{PV\ STC}$	0.2
μ	-0.028
ν	42.9
T_{STC}	25
NOCT	20
A_{pv}	2.245278
P_{pv}	450
$\eta_{inverter}$	0.85

3.4.2. PV model

The PV system performance is simulated using the open-source code OptiCE.[21] The efficiency of the PV system η_{PV} (%) is calculated as:

$$\eta_{PV} = \eta_{PV,STC}\left(1 + \frac{\mu}{\eta_{PV,STC}}(T_a - T_{STC}) + \frac{\mu}{\eta_{PV,STC}}\frac{9.5}{5.7 + 3.8v}\frac{NOCT - 20}{800}(1 - \eta_{PV,STC})G_t\right)\Psi$$

The PV system output is calculated as

$$P_i = A_c G_T \eta_{PV} \eta_{inverter}$$

3.5 Revenue and generation cost

The output of the PV system is directly sold to users (ships) at the retail price (CNY 1.06/kWh) to gain profits.

the return on investment is calculated as:

$$\mathrm{ROI} = \frac{Revenue}{Cost} \times 100\%$$

the levelized cost of electricity is calculated as:

$$LCOE = \frac{\sum_{t=1}^{25} \frac{I_t + M_t + F_t}{(1 + r)^t}}{\sum_{t=1}^{25} \frac{E_t}{(1 + r)^t}}$$

4. RESULTS

4.1 Forecast of shore power demand at Yangshan Port

The construction of Yangshan Deep-water Port is divided into 4 phases. 5 berths with 100,000-tonnage capacity have been built during phase I, with a land area of 1.53 square kilometers, and an annual handling capacity of 2.2 million TEUs; 4 berths with 100,000-tonnage capacity have been built during phase II, with an annual throughput capacity of 2.1 million TEUs; 7 berths with 100,000 to 150,000-tonnage capacity have been built during phase III; the phase IV of Yangshan Port construction started in December 2014, 7 berths with 150,000-tonnage capacity have been built. According to the power meter of auxiliary ship equipment commonly used in China's national standard JTS 155-2012,[19] we estimated the power demand of Yangshan Port as shown in Table 2:

Table 2. Power demand forecast of Yangshan Port

Project	Number of Berth	Capacity (Tonnage)	Ship auxiliary engine power output (kW)	Power Demand (kW)
Phase I	5	100K	11040 (100k Tonnage)	55200
Phase II	4	100k		44160
Phase III	6	100k		66240
	1	150k	15400 (150k Tonnage)	15400
Phase IV	7	150k		107800
Total	**23**			**288800**

4.2 PV deployment layout at Yangshan Port

To meet the power demand of Yangshan Port, at least 288.800 kW of PV capacity needs to be deployed. According to the specifications of the PV modules we selected, 642 thousand PV panels need to be deployed to meet the corresponding demand, which requires 1.44 km^2 of available land or water area. By referring to the "Yangshan Deepwater Port Planning", we measured the unexploited land on Xiaoyangshan Island. As shown in figure 2, the area of 4 unexploited areas of 2.09 km^2 can fully provide space for grounding PV deployment. There

Fig. 2. Available land area for PV deployment at Yangshan Port.

is currently no berth on the north of the port, so the water area can be used to deploy floating PV freely.

4.3 Grounding PV and floating PV technical comparison

Deploying PV panels at different locations will have different impacts on their performance. Worrada's work summarizes the performance improvement of floating PV to grounding PV obtained from previous research.[22] We have selected five values of 2%, 5%, 10%, 15%, and 20% to compare the difference in power generation performance of the two PV systems, as shown in figure 3.

Due to the cooling effect of water, the power generation of Floating PV has been improved compared with grounding PV.

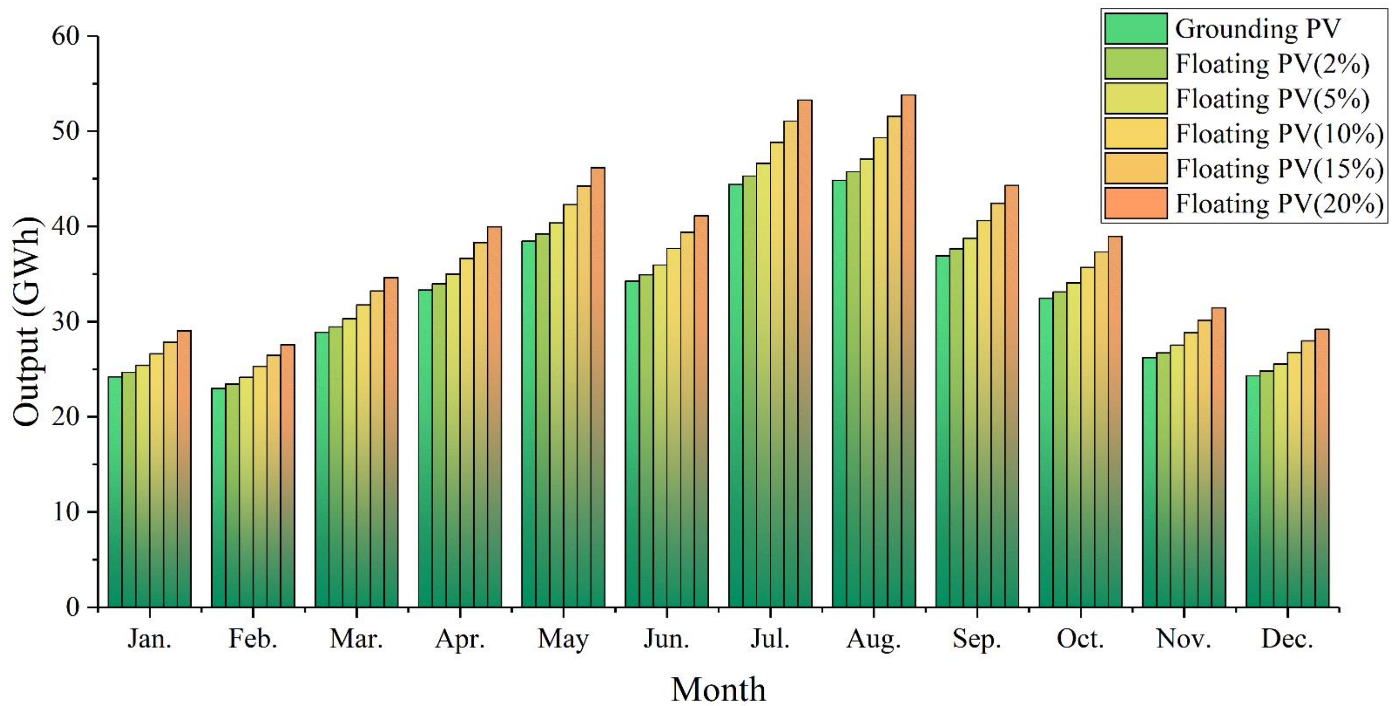

Fig. 3. Monthly output of different PV systems.

4.4 Economic performance comparison between grounding PV and floating PV

4.4.1 System Cost Comparison

Grounding PV and floating PV are different in structure and components, the cost of grounding PV and floating PV will be different consequently. Grounding PV uses mounting structures to be installed on the ground while floating PV needs pontoon and mooring structures. The complicity of the platform of floating PV will rise the system cost. Table 3 shows a comparison of grounding PV and floating PV costs:

In our estimation, the system cost of Floating PV is 8.53 Yuan/W, which is 11% higher than Grounding PV.

Table 3. Cost breakdown of floating and ground PV system.

	Component	**Unit**	**Floating PV**	**Grounding PV**
FRONT FEE	PV modules, Standard 450W module	Yuan/W	2	2
	Supports/integration	Yuan/W	1.5	0.3
	Inverter	Yuan/W	0.3	0.3
	Wirings	Yuan/W	0.2	0.2
	Engineering(design, transport, and assembly, install)	Yuan/W	0.9	0.9
	Combiner box	Yuan/W	0.1	0.1
	Insurance cost	Yuan/W	0.035	0.035

	Grid connection fee	Yuan/W	0.5	0.5
	GROSS FRONT FEE INVESTMENT	Yuan/W	**5.535**	**4.335**
CHANGE INVERTER	Inverter replacement	Once in 25 years	0.3	0.3
YEARLY FEE	O&M cost	Yuan/W	0.04	0.04
	land rent	Yuan/m^2	0	0.024
	Loan duration		5 years	5 years
	Interest rate		8%	8%
ANNUITY		Yuan	1.39	1.12
YEARLY COST for the first 5 years		Yuan	1.43	1.16
YEARLY COST for following 6-25 years		Yuan	0.04	0.06
AVERAGE PRICE PER WATT		**Yuan/W**	**8.53**	**7.66**

4.5 Profitability and generation cost comparison

We use lifetime revenue, ROI, and LCOE to compare the economic performance between grounding PV and floating PV. The result is shown in figure 4. It can be seen that due to the improvement in system output, all floating PVs earn more money than grounding PV during their life span. But this does not mean that the ROI of floating PV is always higher. It can be found that when the efficiency of floating PV is increased by 20%, its ROI will be higher than that of grounding PV. This is because the system cost of floating PV is higher. When the performance improvement of floating PV is less than 15%, the increase in power generation cannot make up for the cost increase.

The difference in performance and cost will also lead to a difference in generation costs. It can be seen from figure 4 that although the power generation of grounding PV is the least among all systems, its power generation cost is the second-lowest, only 0.32 RMB/kWh. Only the power generation cost of floating PV with a performance increase of 20% is lower than that of grounding PV.

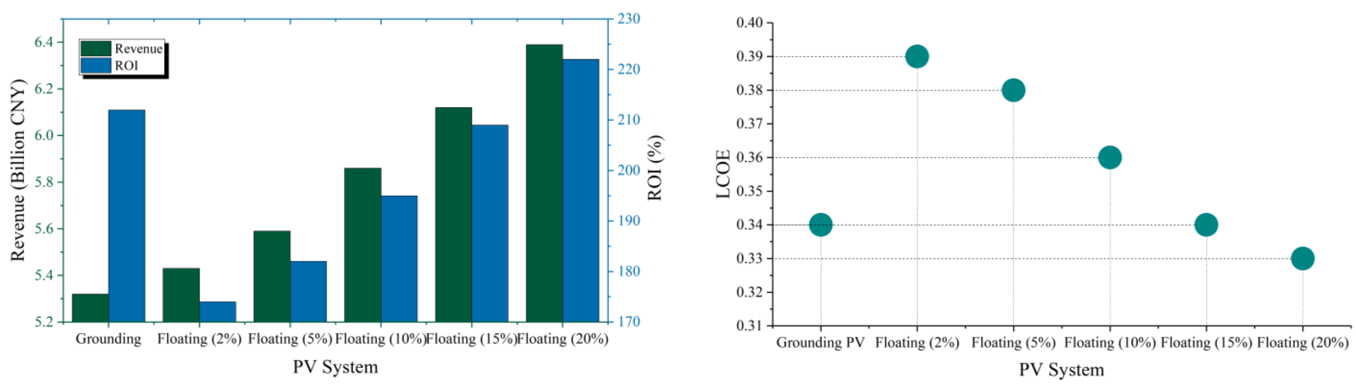

Fig. 4. Economic performances of different PV systems. Left, the lifetime revenue. Right, The levelized cost of electricity

5. DISCUSSION AND CONCLUSION

China's shore power system is developing rapidly. As of the end of 2019, more than 5,400 port shore power facilities have been built. However, the utilization rate of shore power has been low, which at many ports is still less than 10%.[23] High electricity price is one of the main problems hindering the use of shore power. Take Yangshan Port as an example, the electricity buying price for Yangshan Port is CNY 1.5 per kWh, but the selling price is limited to CNY 1.06 per kWh due to relevant policy. The port loses 45 cents for every kWh electricity selling.[24] Switching to shore power for calling ships will undoubtedly help reduce pollutant emissions and improve environmental quality at ports, but high electricity prices will cool the enthusiasm for shore power promotion down.

The results of this paper show that the use of PV systems can significantly reduce power generation costs. Compared with current electricity prices, grounding and floating PV systems can reduce electricity costs to CNY 0.34 and 0.33 per kWh respectively. This can directly enable the port to avoid the losses, and Increase the motivation for prompting shore power.

An excellent advantage of arranging PV at ports is that the wide water area can be used for floating PV systems, which can bring two obvious benefits. The demand for shore power is intensive, which requires large available land to deploy PV panels. Although the land at Yangshan Port can meet this demand when the port has limited available area will bring restrictions for PV deployment. Nevertheless, the deployment of floating PV can avoid such restrictions and relevant costs. Moreover, our results show that due to the cooling effect of water, the power generation efficiency of floating PV is improved, but because the system cost is higher, only when the power generation efficiency of floating PV is increased by close to 20% can it make up for the rising cost. Therefore, there are trade-offs between performance and cost, and the appropriate PV power generation system should be selected according to the actual situation during specific deployment.

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