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Techno-economic Analysis of Roof-Mounted Solar Photovoltaic in University Campus

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ABSTRACT

Solar photovoltaic technology is a mature, stable and sustainable energy solution with important social and economic benefits. This study aims to investigate the technical and economic feasibility of installing solar PV systems on the building roofs in the university campus. The techno-economic analysis was carried out under three installation scenarios: PV modules parallel to the pitched roof, PV modules aligned at the optimal tilt angle on flat roof and pitched roof, respectively. The results show that, the flat roof has the potential installed capacity of 3.82 MW with an annual generation capacity of 4.51 GMh, while the pitched roof has the potential installed capacity of 2.45 MW and 2.64 MW with an annual generation capacity of 2.89 GWh and 3.11 GWh depending on two installation orientations and tilt angles, respectively. The economic analysis of the above three scenarios shows that all PV systems are in profit and positive net cash flow in year 5 for PV projects installed at optimal tilt on flat roofs and parallel to the roof on pitched roofs, and positive net cash flow in year 6 for PV projects installed at optimal tilt on pitched roofs.

Keywords: Solar photovoltaic; Campus PV; Technical feasibility; Economic assessment

1. Introduction

In the context of rapid development of global low-carbon economy and intense stress of global warming, China has already committed to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060. As a clean and sustainable energy source, bolstering development of solar power is an alternative strategy to cope with climate change issues.

Solar photovoltaic (PV) modules have been well researched and extensively utilized on walls and roofs of various buildings due to easy installation and operation[1-2]. University campuses have vast residential and academic buildings, and many of these building roofs are large and good enough to fit solar PV systems. The available area of PV rooftops can be estimated through Geographic Information System (GIS), either by sampling a small portion of the area to estimate the potential PV area, or by geostatistics, modeling, or machine learning based methods to estimate the available area of a house[6]. In this study, technical and economic feasibility of installing solar PV systems on the building roofs in the university campus was carried out by manually eliminating the unavailable roof areas.

2. Method

2.1 *Study case*

The study case, Qilu University of Technology (36.559°N.116.804°E), is located in Changqing District, Jinan City, Shandong Province, China, covering an area of 1.53km^2.

In this study, satellite image data was obtained from Wish3D Earth and the potential areas of the roofs in the satellite images were retrieved by manual inspection. Hourly global horizontal radiation, diffuse horizontal radiation, tilted plane global radiation, ambient temperature, and wind speed data were obtained from METEONORM Global Meteorological Database. The input data for the PV project calculation are as follows.

Table 1

Photovoltaic power generation calculated input data

Parameter	Unit	Value
length	m	1.755
width	m	1.038
altitude	m	0.035
$\eta_{pv\text{-}stc}$	%	19.5
μ	%/℃	-0.27
T_{STC}	℃	25
NOCT	℃	20

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P	kw	0.355
β_n	°	16.51
ψ_s	°	42.59
η_{BOS}	%	80.56
PV system's lifespan	year	25
K	%	0.945

2.2 *Tilt angle and packing factor of PV modules*

2.2.1 Flat roof

In order to minimize the impact of mutual shading among PV modules, 3pm. on the local winter solstice is used for the calculation of PV module spacing[3]:

$$D_f=L\cos\varepsilon+L\frac{\sin\varepsilon}{\tan\beta_n}\cos\varphi_s$$

where D_f is the spacing between adjacent photovoltaic panels, m; L is the length of PV panels, m; ε is the title angle of PV array,°; βn is the sun's altitude angle at 3pm on the winter solstice,°; φ_s is the sun's azimuth angle at 3pm on the winter solstice (Fig. 1).

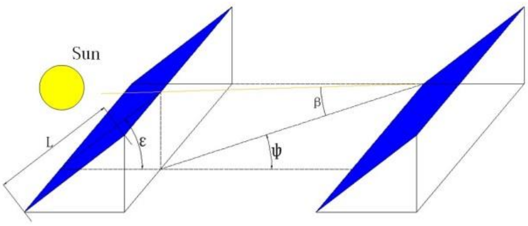


Fig. 1 Schematic diagram of PV module installation on a flat roof

2.2.2 Pitched-roof

Two different installation methods on the pitched roof were adopted in the present study. The first one is PV modules installed parallel to the roof, which has no problem of mutual shielding of PV modules. The second is to install PV modules with a certain spacing at the optimal inclination angle. Two scenarios has been investigated in order to find out the better installation method with higher technical and economic benefits.

Scenario A: higher utilization of potential roof areas by laying PV modules parallel to the sloping roof;

Scenario B: higher efficiency of each PV module by laying PV modules on a sloping roof at an optimal angle of inclination.

Under scenario A, there is no shielding phenomenon between PV modules and potential roof areas are fully utilized, so Packing Factor(PF) is not considered. In contrast, shadowing effect between PV modules will deteriorate the application under scenario B, and PF must be considered as a necessary factor. The minimum pitch of adjacent PV panels on a pitched roof is different from that of a flat roof, taking into account the angle between the roof and the ground, and is calculated by following formula:

$$D_b=L\cos\varepsilon+L\frac{\sin\varepsilon\,(\cos\varphi_s-\tan\theta\tan\beta_n)}{\tan\beta_n-\cos\varphi\tan\theta}$$

D_b is the spacing between adjacent photovoltaic panels in scenario B, m; and θ is the Angle between the roof and the ground, ° . (Fig. 2)

$$PF=\frac{L}{D}$$

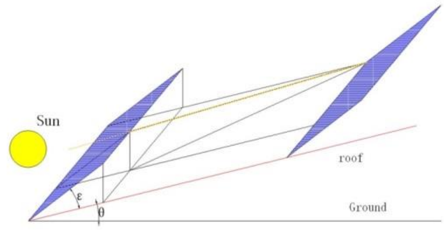


Fig. 2 Diagram of mounting PV modules on a pitched roof at an optimal tilt angle

2.2.3 Potential capacity

The potential capacity is calculated as

$$capacity=\frac{area_{potential}}{area_{PV}}\times PF\times P$$

Where capacity is the potential capacity of the PV system, MW; $area_{potential}$ is potential area of the roof, m^2; $area_{PV}$ is the potential area of PV panels, m^2; P is the wattage of the PV panel, W.

The efficiency of a PV system depends on a variety of parameters, such as ambient temperature and wind speed. Therefore, this study uses open source code OptiCE to calculate the efficiency of PV modules[4].

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

Where η_{PV} is the actual working efficiency of the PV module, %; η_{PV-STC} is the working efficiency of the photovoltaic module under standard working conditions, %; μ is the temperature coefficient, %; T_a is the ambient temperature, ℃ ; T_{STC} is the temperature of the photovoltaic module under standard working conditions, ℃; v is the actual wind speed, m/s and NOCT is the nominal operating temperature, ℃.

The efficiency of the system will also affect the power generation of the whole photovoltaic system[5]:

$$E_P=H\times\frac{capacity}{E_S}\times\eta_{BOS}\times\eta_{PV}$$

Where E_P is PV output in the first year, kWh; H is for global irradiation, kWh/m^2; E_S is standard PV test condition, kWh; η_{BOS} is system efficiency of PV modules, %.

The output of photovoltaic modules in the lifespan can be calculated as:

$$E_{total} = \sum_{i=0}^{25} E_P K^i$$

Where E_{total} is the total output of the photovoltaic system during its lifetime, kWh; K is the annual degeneration rate of the PV panels, %. The input data for the PV project calculation are as follows.

2.3 *Cost and* benefit *analysis*

The lifetime cost(*LC*) of a photovoltaic project can be derived from the following equation

$$LC = \sum_{i=1}^{25} \frac{\left(\left(C_{equipment,i} + C_{O\&M,i}\right) \times capacity\right)}{1.05^i}$$

Where $C_{equipment,i}$ is the unit equipment investment and equipment replacement cost in year *i*, CNY; $C_{O\&M,i}$ is the Operations & Maintenance (O&M) cost in year *i, CNY*.

The lifetime PV project revenue is

$$Revenue_k = \sum_{i=1}^{25} \frac{E_{p,i} \times P_k}{1.05^i}$$

Where $Revenue_k$ is the lifetime income under scenario k, CNY; $E_{p,i}$ is the PV output in year i, kWh and P_k is the electricity price under scenario k, W.

Net Present Value (NPV), Internal Rate of Return (IRR) and Return on Investment (ROI) can be expressed by following equations, respectively:

$$\mathrm{NPV}_i = \sum_{i=1}^{i} \frac{R_i}{1.05^i}$$

$$0 = \sum_{i=1}^{25} \frac{R_i}{(1 + IRR)^i}$$

$$\mathrm{ROI} = \frac{NI}{LC} \times 100\%$$

where R_i is the annual net cash flow and *NI* is the lifetime net income.

3. Results and Discussions

3.1 Technical benefits

From Table 1 and the equations in Chapter 2, we can calculate that the potential PV capacity of the flat roof of Qilu University of Technology is 3.82 MW. the annual power generation is 4.51 GMh. When the PV modules are tilted at the optimal angle of inclination, the potential PV capacity of the pitched roof is 2.45 MW and the annual power generation is 2.89GWh; When the PV modules are parallel to the roof, the potential PV capacity of the pitched roof is 2.64MW and the annual power generation is 3.11GWh.

3.2 Economic Benefits

In this study, it is assumed that all the electricity generated by the PV project is used to power the university. The ROI of the PV project on a flat roof is 25.6%, and the ROI of the two cases on a pitched roof is 25.4% and 25.0%. The payback period is 5 years for both the flat roof and the PV module parallel to the pitched roof scenario, and 6 years for the pitched roof scenario with the optimal tilt angle (Fig. 3 Fig. 4).

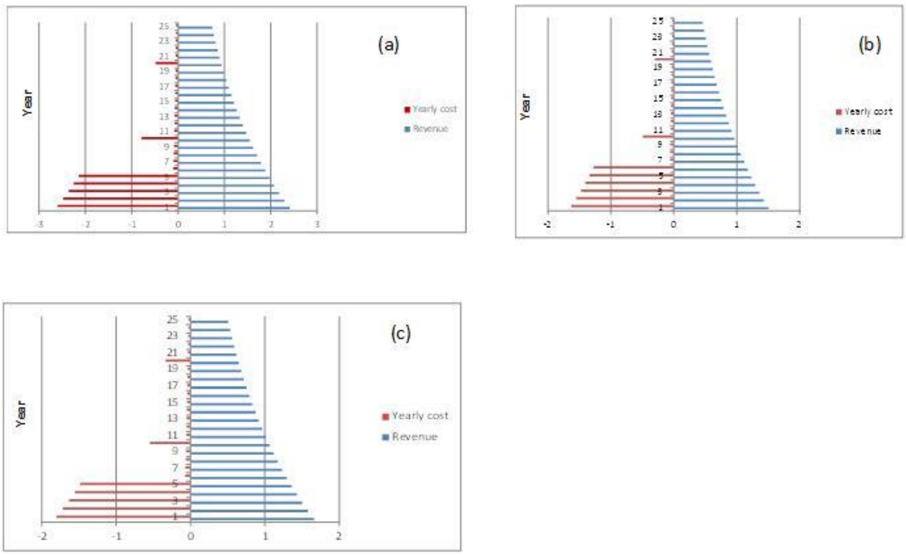
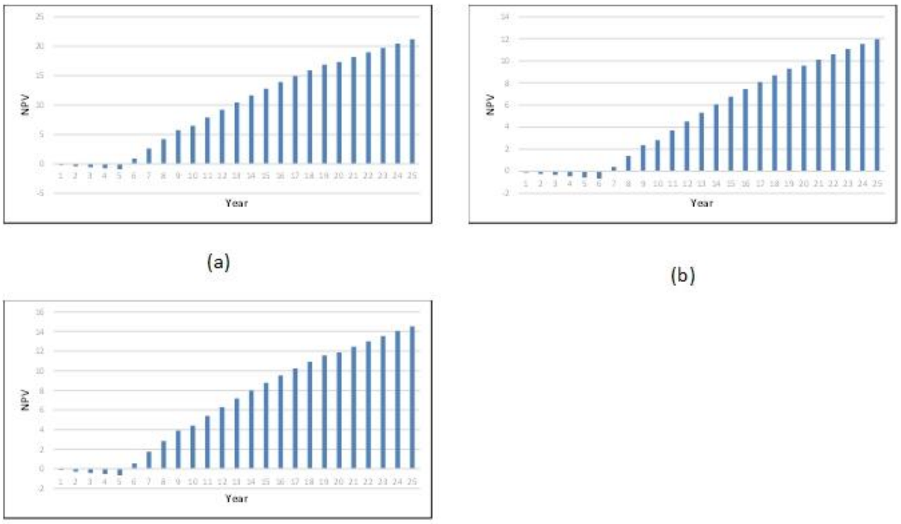


Fig. 3 Comparison of income and expenditure for three types of installations, (a) income and expenditure for the case of flat roof PV modules installed at the optimal tilt angle, million CNY; (b) income and expenditure for the case of pitched roofs installed at the optimal tilt angle, million CNY ; (c) income and expenditure for the case of pitched roof PV modules parallel to the roof,

million CNY.



(a) (b) (c)

Fig. 4 Potential benefits of the PV project at Qilu University of Technology, (a) Cumulative NPV of a flat roof with PV modules installed according to the optimal tilt angle, million CNY; (b) Cumulative NPV of a pitched roof with PV modules installed according to the optimal tilt angle, million CNY; (c) Cumulative NPV of PV modules on pitched roofs parallel to the roof case, million CNY.

Conclusion

In this study, the findings show that the Qilu University of Technology has significant PV potential. The area of solar PV panels on the building is 0.056 km^2 with an annual power production of 7.40 GWh-7.62 GWh and a total income of 5.94M CNY-6.10M CNY in lifetime.

Due to the different utilization rate of solar irradiation, the return on investment of PV projects installed on flat roofs is 0.6%-0.8% higher than that of PV projects installed on pitched roofs. Moreover, due to the different angle of PV module laying on the pitched roof, laying parallel to the pitched roof can improve the utilization of the roof area and lay more PV modules, but the cost will also increase; when the PV module laying angle is the best inclination angle of 30°, it improves the power generation efficiency of each PV module, but the investment payback period increases from 5 years to 6 years.

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