Economic Performance of Building-Integrated Photovoltaics: Building Location and Aspect Ratio

Sappinandana Akamphon[1]

[1] Department of Mechanical Engineering, Thammasat University, Pathumthani 12120, Thailand
*Corresponding Author: sup@engr.tu.ac.th, Tel: 02-564-3001-9, Fax: 02-986-9545

Abstract

This work presents the financial benefit of installing photovoltaics on a building façade, called building-integrated photovoltaics (BIPV), of various building locations and aspect ratios. Typically, photovoltaics tend to be considered overly expensive for use in residential or commercial buildings—the benefit of electricity generation is meager comparative to the cost of photovoltaics. However, it has been shown that BIPV can help reduce the amount of heat gain through walls. This lowers cooling energy consumption in a building, a significant amount especially in a tropical country like Thailand. Using building heat transfer model, this work analyzes the reduction in heat gain and required cooling energy, mapping these into economic performances. This work then provides a guideline for optimal orientation for BIPV at different latitudes and of different building aspect ratios.

Nomenclature

I	Solar irradiance (W)
A	Wall area (m^2)
$Q_{PV\,rad}$	Heat loss from PV by radiation (W)
E_{gen}	Electricity generated by PV (W)
$Q_{PV\,conv}$	Heat transfer by convection at PV (W)
m_{PV}	Mass of PV (kg)
c_{PV}	Specific heat capacity of PV (J/kg-K)
T_{PV}	PV outer surface temperature (K)
T_{sky}	Sky average temperature (K)
T_{surr}	Surrounding temperature (K)
η_{PV}	PV efficiency
$Q_{W\,cond}$	Heat transfer to wall (W)
Q_{gap}	Heat transfer in the gap (W)
h_{air}	Air heat transfer coefficient (W/m2 K)
T_{OW}	Outer wall surface temperature (K)
k_W	Wall thermal conductivity (W/m-K)
L	Wall thickness (m)
M_W	Wall mass (kg)
c_W	Wall's specific heat capacity (J/kg-K)
T_{IW}	Inner wall surface temperature (K)
Q_{room}	Heat transfer into room (W)
T_{room}	Room temperature (K)
C_{cool}	Space cooling expense rate (baht/s)
COP_{AC}	Coefficient of performance of AC unit
P_e	Electricity price (baht/J)

1. Introduction

Photovoltaic has received much attention as an alternative energy source because of its clean operation. However, high cost prevents its widespread use in residential buildings. Furthermore, inexpensive electricity tariff lowers its financial benefit of electricity generation.

However, there is a second benefit of BIPV—its shading ability. It has been shown that up to 60% of electricity cost in urban buildings arises from space cooling, especially in tropical area. By blocking direct solar radiation incident on the walls, BIPV leads to heat gain reduction which in turn lowers cooling load in buildings. Additionally, an air gap between the installed PV and the wall acts also as insulation and natural convection further reduces the heat absorbed by the wall. This heat gain reduction benefit has been demonstrated in several previous works. [1, 2]

While the heat gain reduction benefit has been studied thoroughly, there has yet to be an attempt to quantify the financial benefit and determine the feasibility of such installation in buildings in various climates. This work evaluates the financial benefit of electricity generated from BIPV along with that of heat gain reduction and attempts to provide a guideline for optimal building aspect ratios and photovoltaic orientations at different latitude.

The guideline should prove useful to building designers and city planner who can easily determine optimal PV installation orientations in various building types regardless of location. The article also provides flexible framework for evaluating feasibility of such installations for under varying electricity tariffs.

2. Assumptions and Methodology

The objective of this work is to show the significance of reduced heat gain to the economic performance of solar panel installation and also to determine building characteristics that lead to the most viable solar panel installation. In this section, baseline assumptions regarding the buildings, solar panel installations, and economic performance evaluation must be addressed.

2.1 Building specifications and operation

The building in consideration is assumed to be a typical commercial or industrial building which is utilized mostly during the day. The building walls and roof are modeled as 15 cm concrete. The window-to-wall ratio is 15%. Each floor is 5 cm thick. Three building aspect ratios will be considered—2:1, 1:1, and 1:2. The aspect ratio is defined in this work as the ratio between the lengths of the north and east walls.

Building location will also play important role in economic performance of a PV installation since it is directly related to solar incident angle and the surrounding temperature. In this article, 3 locations are modeled based on their respective latitudes—Singapore (1 N), Bangkok (13 N), and Taiwan (23 N). No cities further north from Taiwan is modeled because of their temperate climate and little need for space cooling. It is also assumed that there is no heat gain due to penetration or bioheat. The air conditioning (AC) unit in all rooms are set to 25 C (298 K) and they have COP of 3.5. The operating time of the AC is between 8 am – 5 pm.

2.2 PV installation assumption

The modeled characteristics and costs of solar panels and inverters are listed in Table 1 and

Table 2. The parameters are used to model the amount of electricity generated from solar panel installations.

Table 1: Modeled solar panel characteristics and cost based on Samsung LPC250S panel

Maximum Power	250	W
Dimension (LxWxH)	1.9x1.3x0.05	m
Unit Cost	15000	baht

Table 2: Modeled inverter characteristics and cost based on Fronius IG Plus-5.0

Capacity	5	kW
Unit Cost	100000	baht

The solar panels modeled here are fixed and face outward normal to the building surface on which they are installed, and they completely cover the surface, leaving only window area exposed to the sun. The panels are assumed to be directly connected to a power grid, eliminating the need for batteries. The buildings are assumed to have no shades from other buildings or surrounding trees. The solar panels and inverters are assumed to have lifetime of 20 years.

2.3 Building heat gain calculation

This article uses heat transfer equations to calculate cooling load of building with and without photovoltaic façade developed by [3, 4]. The equations are divided into energy balance equations at the PV and wall as follows.

$$\alpha IA = Q_{PV\,rad} + Q_{PV\,conv} + E_{gen} + m_{PV} c_{PV} \dot{T}_{PV} \quad (1)$$

$$Q_{PV\,rad} = A\sigma\varepsilon(T_{PV}^4 - T_{sky}^4)$$

$$Q_{PV\,conv} = h_{air} A(T_{PV} - T_{surr}) \quad (2)$$

$$E_{gen} = \eta_{PV} aI$$

At the PV, the solar irradiance provides the power input. The incident solar irradiance I at any time during the day can be calculated using the incident angle and solar irradiance according to building latitude. The heat losses consist of heat radiated back into the surrounding area and natural convection, while energy that has been absorbed is converted to electricity and heat.

$$Q_{PV\,rad} = Q_{W\,cond} + Q_{gap} + m_W c_W \dot{T}_W \quad (3)$$

$$Q_{W\,cond} = \frac{k_W A(T_{OW} - T_{IW})}{L} \quad (4)$$

$$Q_{gap} = Ah_{gap}(T_{OW} - T_{surr})$$

$$Q_{room} = h_{air} A(T_{IW} - T_{room}) \quad (5)$$

At the wall, the heat that has been absorbed by the PV radiates to the wall through the air gap in between. There is also heat loss due to natural convection (Q_{gap}). The heat absorbed by the outer wall raised its temperature, gets conducted to the inner wall, and is transferred inside the room by convection.

2.3 Economic performance evaluation

The heat gain into room Q_{room} is used to calculate the space cooling expense rate by the following equation.

$$C_{cool} = P_e E_{cool} = \frac{P_e Q_{room}}{COP_{AC}} \quad (6)$$

In this article, the space cooling expense is accumulated as an annual payment. The electricity price is assumed to be 8.33E-7 baht/J (which is 3 baht/kWh).

Additionally, in the first year, there is an investment in the PVs and inverters.

On the benefit side, there is the revenue from sale of generated electricity R_e and the saving from reduced cooling energy requirement R_{saving}. Thus, the revenue rate is

$$R = R_{saving} + R_e$$

$$R_{saving} = P_e \eta_{AC} (Q_{room\ noPV} - Q_{room}) \qquad (7)$$

$$R_e = P_e E_{gen}$$

The difference in cooling load translates to cooling energy cost saving, which will be used in combination with the investment in BIPV to calculate internal rates of return (IRR). The IRR can be calculated using the equation

$$0 = \sum_i \frac{R - C_{cool}}{(1-irr)^i} \qquad (8)$$

In this article, it is assumed that electricity price and efficiencies of PV and air conditioning unit remain constant over the lifetime of the PV. Therefore, with an exception of the investment in the first year, cash flows of the subsequent years are always constant.

3. Results and Discussion

After implementing the heat transfer equations and solve for the temperature and corresponding heat gain through walls using Microsoft Excel. The results are broken down and compared by category. First, the comparison of economic performances of installation by locations is discussed. The effect of aspect ratio is afterwards investigated. Underlying reasoning for the results are also discussed to provide insights into the problem.

3.1 Economic performance by location

The result shows that for the building in Singapore and Bangkok, the BIPV orientation that gives the highest rate of return is east, as illustrated by Fig. 1. For building in Taiwan, however, the optimal orientation is southward because it faces the sun throughout the day for the most part of a year.

While it may seem at first that the optimal installation for buildings in tropical area would be the west due to due to the usually intense heat in the afternoon sun, it is not so in this case. As the air conditioning unit is operational only until 5 pm and therefore the afternoon sun and heat can only affect the west wall in the afternoon. The east wall, on the other hand, has soaked up the heat from the sun all morning, part of which is released into the room in the afternoon.

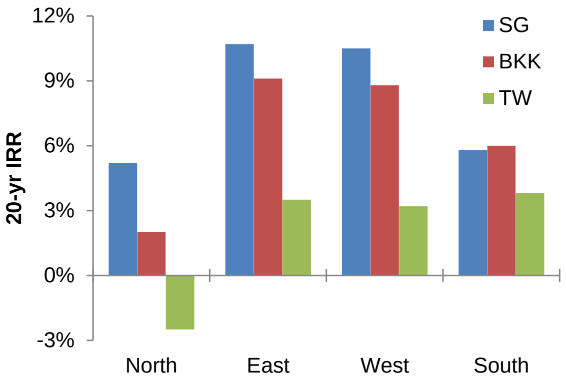

Fig. 1 Comparison of IRRs of PV installations on building in Singapore, Bangkok, and Taiwan.

3.2 Economic performance by aspect ratio

The aspect ratio affects the rate of return of various PV installations differently because the ratio affects the wall size and therefore the amount of heat gain through that wall. The larger the wall, essentially, the higher heat gain through and therefore potentially more heat gain reduction benefit. It must, however, also be considered that larger wall also requires larger amount of PVs to cover it.

To focus on the effect of aspect ratio, we investigate the economic performance of PV installations on 3 buildings with 1:2, 1:1, and 2:1 aspect ratios all located in Bangkok.

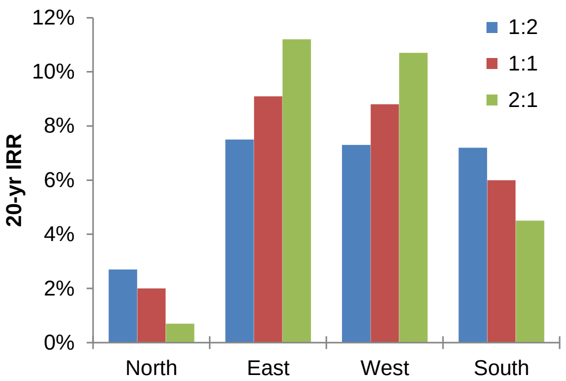

Fig. 2 Comparison of IRRs of PV installations on building with various aspect ratios.

Fig. 2 shows that, for Bangkok, as the walls size decreases, the rate of return of a PV installation improves. This is true for all walls. For example, as the south wall size decreases (aspect ratio goes from 2:1 to 1:1 to 1:2), the IRRs improve from 4.5% to 6% to 7.2% respectively. The same is true as the east wall size decreases (aspect ratio goes from 1:2 to 1:1 to 2:1), the IRRs increases from7.5% to 9.1% to

11.2%. This is because a smaller wall requires smaller investment on PVs and inverters, while the heat gain reduction and electricity generation are still significant enough to provide revenue and better return.

4. Conclusion

This paper has determined the guideline for optimal BIPV orientation in various latitudes and for different building aspect ratios. It has been shown that, even without additional incentives, the benefit of heat gain reduction and electricity generated can make BIPV an attractive investment. For example, in the case of Bangkok east wall 2:1 aspect ratio, the IRR is 11.2%--a rather respectable return. It also shows that locations and building aspect ratios are significant contributing factors to selecting the optimal orientation. Depending on the sun path at the location, installing PV on the wall that is most exposed to the sun provides the best return. Additionally, results show that smaller wall provides better return for the same size building. Therefore, as a guideline, install PV on a building wall that is small and most exposed to the sun to gain the highest economic benefit.

5. References

1. Oliver, M. and T. Jackson, Energy and economic evaluation of building-integrated photovoltaics. Energy, 2001. 26(4): p. 431-439.
2. Fanney, A.H., B.P. Dougherty, and M.W. Davis, Measured performance of building integrated photovoltaic panels. Journal of solar energy engineering, 2001. 123: p. 187.
3. Davis, M.W., A.H. Fanney, and B.P. Dougherty, Measured versus predicted performance of building integrated photovoltaics. Journal of solar energy engineering, 2003. 125: p. 21.
4. Yang, H., et al., Grid-connected building-integrated photovoltaics: a Hong Kong case study. Solar energy, 2004. 76(1-3): p. 55-59.
5. Henson, J.W.C., CLIMATE AND LATITUDE EFFECTS FOR BIPV SHADE ELEMENTS.
6. Yang, H., J. Burnett, and J. Ji, Simple approach to cooling load component calculation through PV walls. Energy and buildings, 2000. 31(3): p. 285-290.
7. Wang, Y., et al., Influence of a building's integrated-photovoltaics on heating and cooling loads. Applied energy, 2006. 83(9): p. 989-1003.
8. Crawley, D.B., et al., Contrasting the capabilities of building energy performance simulation programs. Building and Environment, 2008. 43(4): p. 661-673.
9. Scheuer, C., G.A. Keoleian, and P. Reppe, Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energy and buildings, 2003. 35(10): p. 1049-1064.
10. Yezioro, A., B. Dong, and F. Leite, An applied artificial intelligence approach towards assessing building performance simulation tools. Energy and buildings, 2008. 40(4): p. 612-620.
11. Erickson, V.L., et al. Energy efficient building environment control strategies using real-time occupancy measurements. 2009. ACM.