121st ASEE Annual Conference & Exposition
Indianapolis, IN
June 15-18, 2014
Paper ID #8615

BIPV Roof Tiles: Effect of Locations on Energy Cost Savings

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Abstract

Building Integrated Photovoltaic (BIPV) materials have a great potential of being used as a source of renewable energy for buildings. The purpose of this study was to determine the correlation between energy savings due the use of BIPV roof tiles and heating and cooling degree days. A total number of 35 sites, 7 each from five climatic zones in the United States, were randomly selected for the study. The data for heating and cooling degree days was collected from published sources. Energy cost savings estimates for BIPV roofing at 35 different locations were done using a simulation model developed by National Renewable Energy Laboratory. A general linear model was used to find out the effect of heating degree days, cooling degree days, and location of the buildings on energy cost savings.

The results of the analysis indicate that energy cost savings for residential buildings using BIPV roof tiles are affected by heating degree days and location of a building. Cooling degree days did have any relationship with energy cost savings.

Key words: Building Integrated Photovoltaic, Cooling Degree Days, Energy Cost Savings, Heating Degree Days, Residential Buildings

Introduction

Building Integrated Photovoltaic (BIPV) is a renewable energy technology with a promise. It can be effectively used to replace conventional building elements such as roof shingles or curtain walls to work as part of the building envelope as well generate energy for the building. Energy is generated using photovoltaic (PV) panels that are integral part of the building component. The basic premise of the technology is to combine the power generation of PV within conventional building elements such as roof, curtain walls, window shades, and other products. In an attempt to provide an aesthetically pleasing roof or curtain wall, various companies have introduced PV tiles that integrate with standard building materials. This system basically uses crystalline silicon PV cells built into modules which integrate with roof shingles or curtain walls. The PV array is part of the building's roof, wall, or windows. These arrays directly convert solar radiation to electrical energy. A residential PV system can be can be hooked up with utility grid, making it possible to export the excess energy to the utility company[1].

Even though BIPV technology has been in existence for over a decade, cost issues have slowed down wide-spread acceptance and installation of the systems. A study on cost-effectiveness of BIPV roof tiles, in comparison with asphalt roof shingles, for residential buildings was conducted by Choudhury & Baladhaputrini[2]. The results of the study demonstrated that even though the use of BIPV roof tiles results in considerable saving in energy costs for the residential buildings, the systems were not economically attractive for use in residential buildings in the United States at current costs of materials and installation.

The present study is an extension of the previous study done by Choudhury & Baladhaputrini[2]. It investigates the factors of energy cost savings for residential buildings that use BIPV roof tiles. Different factors of energy savings were taken into consideration for the study. It was hypothesized that net energy savings of a residential building by using BIPV roof tiles is affected by the climatic location of a building, and the number of heating and cooling degree days of the location.

Review of the Literature

Photovoltaic Cells

BIPV systems simply integrate photovoltaic (PV) cells into the building envelope. PV cells are in use for quite some time for harnessing solar energy. The technology is recognized as an important approach to generate an environmentally friendly, sustainable, and clean energy to replace fossil fuels[3].

Photovoltaic cells (PV) are made by joining P and N type semi-conductors. P types contain positive ions, while the N types contain negative ions. These ions produce an environment necessary for flow of electrical current within the cells. Current generated by the cells is DC, which has to be converted to AC by using an inverter.

PV cells were first used commercially in the late 1950s to energize communication satellites[4]. Gradually, the practical application of the technology expanded to include building industry. The benefits of using PV energy compared to fossil fuel energy include (1) autonomy, (2) reliability, (3) sustainability, and (4) zero emission. The quantity of energy savings due to installation of BIPV systems, however, may be affected by the geographical location of the building.

Building Integrated Photovoltaic (BIPV) Cells

PV cells can be woven into building components such as wall and roof, making them an integral part of the building. Building Integrated Photovoltaic (BIPV) systems activate the PV system very efficiently by utilizing PV cells as surface materials of buildings[5]. The system assumes multi-faceted roles by replacing conventional exterior walls, roofs, windows, and shading devices.

BIPV systems for buildings can be either be stand-alone or connected to grid. Grid-connected systems are advantageous in the sense that any surplus energy is exported to the utility grid, eliminating the need for on-site batteries. The owners are thus able to sell excess energy.

Cost-effectiveness of BIPV Systems

Despite some significant advantages of using PVs to produce energy, the manufacturing and installation costs of the systems were higher than that for conventional sources of energy in the past decade[6]. A study done in the mid-2000s provides similar report related to cost-effectiveness of the technology[4]. Another study conducted by Muhida *et al.*[1] also fails to offer any encouraging evidence in support of the BIPV systems as far as costs are concerned. The authors, however, conclude that "break event (sic) point for this system is still far from our wishes, but this system gives a contribution in reducing air pollution and promoting the clean energy (p. 698)."

Li and Lam[3], however, report some positive economic aspects of using BIPV facades for a 40-storey office building in Hong Kong. Their results indicate that when incorporated properly with daylight, the overall simple monetary payback for installation of BIPV systems would be 6 ½ years. This is remarkable considering the high first cost of the systems. The authors, of course, limit the findings only to commercial buildings.

There are some optimistic viewpoints regarding cost-effectiveness of BIPV systems. Davis[7], using what he calls an experience curve, reports that the price of PV cells decreased by 82 per cent over a period of one and half decades. Assuming a continuation of this trend, the author predicts that the production cost of BIPV-generated energy will be comparable to that of fossil fuel electricity by 2020.

Factors Affecting BIPV Systems

The intensity of solar radiation received by the PV cells is the driving force behind power production by BIPV systems. There are a number of variables that affect this intensity. They include (1) solar altitude, (2) solar azimuth, (3) outdoor dry-bulb temperature, (4) shading, (5) dirt accumulation on the surfaces, and (6) efficiency of the cells[4]. Solar altitude and azimuth, and outdoor dry-bulb temperatures vary according to geographical setting. It is, therefore, likely that quantity of energy savings due to installation of BIPV systems, may be affected by the climatic regions, and heating and cooling degree days of a location.

Methodology

Data Collection Procedure

Energy performance of BIPV roof tiles in different climatic locations of the United States was required to be ascertained for the study. This was done through simulation by using Solar Advisor Model (SAM), also known as System Advisor Model, developed by the National Renewable Energy Laboratory[8].

SAM is a performance and economic model designed to facilitate decision making for people involved in the renewable energy industry. The software makes performance predictions for grid-connected solar systems, small wind and geothermal power systems, and economic estimates for distributed energy and central generation projects. It calculates the cost of generating electricity based on information provided about a project's location, installation and operating costs, type of financing, applicable tax credits and incentives, and system specifications. SAM also calculates the value of saved energy due to the use of a BIPV system.

All data related to BIPV roof tiles was collected by using SAM. The data included cost of BIPV roof tiles including their installation for all locations, operation and maintenance costs, cost of auxiliary devices such as inverters, and energy savings.

Location

Seventy locations were selected from the 5 different climatic zones of the United States, 35 each for buildings using BIPV roof tiles and asphalt roof shingles. The climatic zones are: (1) Zone 1 (Cool), (2) Zone 2 (Temperate), (3) Zone 3 (Moderately temperate), (4) Zone 4 (Hot and arid), and (5) Zone 5 (Hot and humid).

Prototype Residential Building

A simple prototype residential building was designed by the author for the study. The roof area of the building was 1680 sq. ft. Data on different variables was collected for the same building, assumed to be constructed in all the selected locations. Data collection for buildings using BIPV roof tiles was done using SAM.

Annual incident energy striking a roof surface is a function of solar altitude and azimuth angles. SAM selected the part of the roof that would contribute to energy savings when BIPV roof tiles were installed. Figure 1 shows the roof area selected by SAM for this purpose. Cost comparison was done based on only this part of the roof.

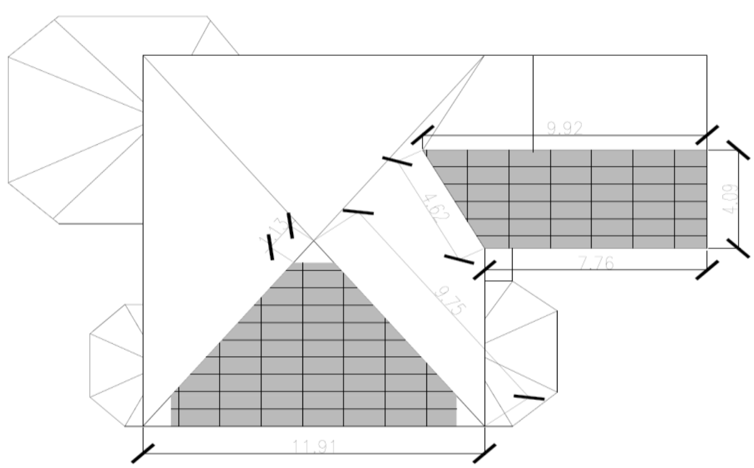

Figure 1. Roof plan of prototype building showing the location of BIPV roof tiles

Variables

Energy savings (ENERGY): These are the net savings in electrical energy costs for a building using BIPV systems, during the first year of its operation. The variable was measured in US Dollars.

Location (LOCATION): It is the climatic zone in which a residential building was located. This is also a categorical variable with five different levels, (1) ZONE 1, (2) ZONE 2, (3) ZONE 3, (4) ZONE 4, and (5) ZONE 5.

Annual Cooling Degree Days (CDD): A cooling degree day is a difference of 1°F between balance point temperature and average daily outdoor dry-bulb temperature of a location. When this difference is higher than the balance point temperature, it is one cooling degree day. The sum of this difference for a year is the annual cooling degree days for the location.

Annual Heating Degree Days (HDD): A heating degree day is also a difference of 1°F between balance point temperature and average daily outdoor dry-bulb temperature of a location. When this difference is lower than the balance point temperature, it is one heating degree day. The sum of this difference for a year is the annual heating degree days for the location.

Findings and Discussions

Energy Savings

Solar Advisor Model was used to find out the energy generated by BIPV roof tiles of a proto-type residential building for 35 different locations in the United States. Average annual energy savings was calculated for all sites using the cost of electrical energy in those regions. The system generated a considerable amount of energy (Table 1), resulting in a substantial saving in energy costs (Table 2).

Table 1. Annual energy output (in kWh/kW peak rating) from BIPV roof tiles installed in prototype residential buildings at 35 locations

Loc.	Annual Energy	Loc.	Annual Energy	Loc.	Annual Energy	Loc.	Annual Energy	Loc.	Annual Energy
1	4000	8	4100	15	3900	22	4800	29	4700
2	4500	9	3800	16	3700	23	4000	30	4200
3	3800	10	4800	17	3900	24	4100	31	4500
4	3500	11	4200	18	3900	25	5200	32	4200
5	3900	12	4000	19	3900	26	4700	33	4300
6	4300	13	4900	20	3800	27	4100	34	4900
7	4200	14	4900	21	5200	28	4200	35	4200

Table 2. Average annual energy savings (in US $) for prototype residential building using BIPV roof tiles at 35 locations

Loc.	Annual average	Loc.	Annual average	Loc.	Annual average	Loc.	Annual average	Loc.	Annual average
1	939	8	1077	15	1010	22	1208	29	1199
2	1069	9	978	16	997	23	1062	30	1118
3	906	10	1190	17	911	24	1093	31	1146
4	890	11	1112	18	1040	25	1275	32	1102
5	1037	12	1049	19	1038	26	1164	33	1119
6	1069	13	1216	20	972	27	1076	34	1226
7	1005	14	1203	21	1290	28	1101	35	1100

Test of the Hypothesis

The hypothesis was also tested using a General Linear Model using SPSS statistical package. This test was done using the data only from 35 locations where BIPV roof tiles were used for the residential buildings. The following model was used for the analysis:

$$ENERGY = \beta_0 + \beta_1(LOCATION) + \beta_2(CDD) + \beta_3(HDD) + e \quad \text{Eqn. (1)}$$

Where ENERGY = net energy savings cost, LOCATION = climatic location of the building, CDD = annual cooling degree days, HDD = annual heating degree days, β_0 = intercept, β_1, β_2, and β_3 = regression coefficients, and e = error term.

The results of the analysis are shown in Table 3.

Table 3. Summary of statistical analysis using ENERGY as dependent variable

Variables		Intercept	Regression Coefficient	t-value	p-value
Intercept		1423.61		13.61	<0.0001
CDD			0.011	0.66	0.52
HDD			-0.05	-3.23	0.003
LOCATION	ZONE 1		-72.26	-1.56	0.13
	ZONE 2		-199.71	-3.87	0.001
	ZONE 3		0*		
	ZONE 4		-141.44	-2.36	0.03
	ZONE 5		-222.01	-2.81	0.009
F = 6.39 p-value: <0.0001		Model R^2 = 0.58		Adjusted R^2 = 0.49	

* This parameter was automatically set to zero by SPSS.

F-value of this model was found to be 6.39, which is also statistically significant at less than the 0.0001 level. However, predictive efficacy of this particular model was not found to be very high with an adjusted value of 0.49. But such values are considered to be satisfactory related to empirical studies in social sciences[9]. The independent variables included in the model explained about 46 percent of the variance.This means that 49 percent of the variances in energy savings (ENERGY) are explained by the variables included in the model.

The results indicate that net energy savings has a statistically significant relationship with almost all the climatic zones (LOCATION) except ZONE 1 (cool zone), at the level of significance of less than 0.05. It means that the savings in energy cost would be significantly different for buildings using BIPV roof tiles with respect to climatic regions in which they are located.

HDD (annual heating degree days) was also found to have a statistically significant on net energy savings, at less than the 0.05 level. The results show an inverse relationship exists between HDD and Energy, which means that higher the number of annual degree days, lower is the amount of energy cost savings. However, CDD was not found to have any statistically significant relationship with ENERGY.

Conclusions

Use of BIPV systems in the building sector is receiving immense interest nowadays in order to make the buildings able to supply their own energy requirements. This study was conducted to identify the factors of energy cost savings for residential buildings using BIPV system.

Computer simulation, which is a non-invasive and powerful tool, was used for assessing the performance of BIPV systems. Particular software selected for the purpose was Solar Advisor Model (SAM) developed by the National Renewable Energy Laboratory. The findings of the study demonstrate that the use of BIPV roof tiles results in considerable saving in energy costs for the residential buildings. The net energy cost savings are correlated with all but one climatic region (LOCATION) in which a building is located and the annual heating degree days (HDD) of that location.

Energy consumption increases with the increase in number of heating degree days. Because of this reason there is obviously an inverse correlation between savings in energy cost and annual heating degree days. But one of the shortcoming of the model is that both weather-dependent and non-weather-dependent (also called baseload) energy consumptions have been lumped together as the dependent variable. This probably has resulted in a predictive efficacy of the model which is not very high. This factor should be taken into account for future studies.

Cooling degree days were also assumed to have a direct relationship with energy consumption in this study. But surprisingly, the results of the study did not indicate any such correlation. One of the reasons maybe the lack of discrimination between weather-related and base energy consumption. The presence of LOCATION as an independent variable may also have affected the outcome; cooling degree days for the different climatic zones may not have quantitatively reflected the zone locations. This factor is also required to be investigated in future research.

This study has got a direct implication for both graduate and undergraduate programs in construction. The results of the study can be a useful tool to construction students, in estimating the domestic heating energy consumption, as well as in applied climate studies and urban air pollution, offering relevant information and support.

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