Design of Roof Morphology for Increased Solar Potential of BIPV/T Systems

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Abstract

This paper presents a design methodology of housing units' roofs for increased solar potential. The basic principle is that complete near-south facing roof surfaces are used as extended surface solar collectors that generate both heat and electricity. The design of the roof surface morphology incorporates the application of building-integrated photovoltaic/thermal (BIPV/T) system that generates electricity simultaneously with useful heat. The methodology is based on an approximate model aiming at finding the correlation between thermal and electrical output of the BIPV/T system, and on analysis of the effect of combinations of tilt and orientation angles of the BIPV/T system. Optimal configurations are applied to the roof of a rectangular housing unit. Gable roof with 45° tilt angle is used as reference. Results indicate a near-constant correlation between thermal and electrical output of a BIPV/T system, under a fixed air fan speed. Some roof shape designs enable increasing the potential of BIPV/T systems by up to 30%, as compared to the reference roof. In addition to optimizing energy production, the integration of photovoltaic/thermal systems in surfaces with different orientations enables a spread of the timing of peak electricity generation over up to 6 hours, which can reduce the mismatch between demand from the grid and supply to the grid.

1. Introduction

Near-south facing roof surfaces are considered optimal for capture of solar energy for electricity and heat generation, and therefore for the integration of photovoltaic/ thermal systems. The basic principle applied in this paper is the utilization of complete near-south facing roof surfaces as extended surface solar collectors that generate both heat and electricity. The technological approach applied is to design the roof outer layer as a building-integrated photovoltaic/thermal (BIPV/T) system - a technology that combines PV modules and heat extraction devices to produce simultaneously power and heat (Tripanagnostopoulos, 2001). Heat extraction from the PV rear surface is usually achieved using the circulation of a fluid (air or water) with low inlet temperature. The extraction of thermal energy serves two main functions, first it is used for space heating and solar hot water applications, and secondly it helps in cooling the PV modules, increasing thus the total energy output of the system (Charron, 2006).

The performance of a PV system depends mainly on the tilt angle and azimuth of the collectors, local climatic conditions, the collector efficiency, and the operating temperature of the cells. During the winter months, the insolation can be maximized by using a surface tilt angle that exceeds the latitude angle by 10-15º. In summer an inclination of 10–15º less than the site latitude maximizes the insolation (Duffie and Beckman, 1991). The PV system is usually mounted at an angle equal to the latitude of the location, to reach a balance between winter and summer production (Kemp, 2006). The orientation of the PV panels affects both the electricity generation and the time of peak generation (Hachem et al, 2011a). PV system orientation can be selected to better match the grid peak load (Holbert, 2009). This can affect the annual value of the produced electricity, especially in locations where electricity value changes with the time of use.

Pelland and Poissant (2006) report that BIPV systems have the potential to supply about 46% of Canada's residential electricity. An open loop air-based BIPV/T system is particularly suited to cold sunny climates such as much of Canada. This air-based BIPV/T concept utilizes circulating outdoor air behind the BIPV panel with the aid of a variable speed fan. The circulated air assists in cooling the panel and recovering heat that can be used for space or water heating.

Covering a complete roof surface with a BIPV/T system has an advantage of forming an outer layer which acts as the weather barrier in addition to producing useful heat and electricity. This principle of using the PV/T panels as outer layer of the roof, instead of being attached to an outer layer (such as shingles) can increase the life time of the system especially if the roof shingles need to be replaced. On the other hand, the implementation of complete homogenous surfaces of BIPV/T enables to avoid joints and connections, and therefore exposed screws/ nails that can lead to rain penetration. This assists in enhancing the overall durability and performance of the system.

The current study is a part of an ongoing research that aims at investigating the effect of design parameters of different housing shape units, isolated and in neighborhood patterns, on their solar potential and energy performance (Hachem et al., 2011a, 2011b). The study presented in this paper focuses on the design of roof shapes of two-storey housing units to increase the thermal and electrical potential of BIPV/T systems that cover complete near-south facing surfaces. The intent is to explore some deviations from the basic hip roof design used commonly for rectangular floor plans, while allowing both architectural flexibility and energy production advantages.

2. Methodology and design approach

This study investigates potential BIPV/T electrical and heat energy production associated with different roof designs of rectangular layouts. The *EnergyPlus* building simulation software (EnergyPlus, 2010) is employed in the simulations using typical annual weather data for Montreal, Canada (latitude 45° N). The ultimate goal is to maximize the combined potential of annual electricity generation and heat production. It should be mentioned, however, that not all heat generation of the BIPV/T system can be useful heat. This depends on other considerations including the temperature of the thermal storage. These considerations are not addressed in this paper.

The investigation consists of three parts. In the first part, an approximate numerical model of an open loop air-based BIPV/T system is employed to determine a relation between potential thermal and electrical energy generation, based on the literature. The objective of this stage is to provide a simple tool for estimating thermal energy potential as a ratio of electrical generation. A gable roof design is assumed in this part. The second stage focuses on studying the effect of varying tilt and orientation on BIPV/T performance per m^2 of an independent roof surface area. The objective is to determine the range of optimal combinations of tilt and orientation angles for annual electricity and heat generation over an assumed heating period. The third stage, which forms the focus of this study, applies the results of the first two stages to actual design of roof shapes, of a housing unit of rectangular floor plan. The design of these roof shapes ranges from the simplest to increasingly complex multi-surface shapes that combine different tilt and orientation angles. The south facing surface of a gable roof is used as reference for comparative evaluation of the BIPV/T potential of all other roof shapes.

2.1. Modelling and simulations

Tools. The development of an approximate model of a BIPV/T system, to correlate electricity and heat generation employs the *MathCAD* 14 software. Simulations carried out in the second and third stages employ the building simulation software EnergyPlus (2010) in conjunction with *Google Sketchup* (2011).

Weather data. The weather files of the building simulation program EnergyPlus are used for the simulations (EnergyPlus: Weather files). The weather data file, which is based on CWEC – Canadian Weather for Energy Calculations, provides hourly weather observations. These observations simulate a one-year period, specifically intended for building energy calculations. The data collected for this typical year includes hourly values for solar radiation, ambient temperature, wind speed, wet bulb temperature, wind direction and cloud cover.

Two design days, a sunny cold winter day (in January) - WDD, and a sunny hot summer design day (in June) - SDD, are used to represent two sunny days with extreme temperature, to study the incident solar radiation on roofs. Additionally, a whole year weather data set is used to estimate the annual electricity generation and winter heat production of the BIPV/T system installed on near south-facing roof surfaces. Weather data of 12 sunny days are selected to represent each month of the year for the BIPV/T numerical model developed in the first stage of the study (see results in Fig. 2).

Solar radiation and shading calculations. Hourly direct solar radiation is computed using the EnergyPlus program. The computation is based on the ASHRAE model of clear sky (ASHRAE, 2003) applied to Montreal (45ºN). This model is the default model used by EnergyPlus to estimate the hourly clear-day solar radiation for any month of the year. The instantaneous solar radiation accounts for the direct beam and diffuse radiation, as well as for radiation reflected from the ground and adjacent surfaces. The shading algorithm handles self-shading geometries. Google Sketchup is employed to generate geometric data for EnergyPlus.

2.2. BIPV modelling

The TRNSYS PV model (or equivalent one-diode model) provided by EnergyPlus is selected to perform electricity generation simulations of the BIPV/T systems in the second and third stages of the study. The TRNSYS model employs a four-parameter empirical model to predict the electrical performance of PV modules (see Duffie and Beckman, 1991).

The current-voltage characteristics of the diode depend on the PV cell's temperature. The model automatically calculates parameter values from input data, including short-circuit current, open-circuit voltage, current at maximum power, etc. (Griffith and Ellis, 2004). For this study, the PV array is selected from EnergyPlus database to provide approximately 12.5% efficiency, under standard conditions. The electrical conversion efficiency decreases by some 0.45% for each °C increase of cell temperature from the temperature under standard conditions. For Montreal, the annual potential of PV electricity generation of south facing surfaces at latitude tilt angle is about 1200 kWh per kW_{peak} of installed PV (NRCan, 2007).

3. BIPV/T simple model

3.1. Approximate model

A transient quasi-two-dimensional finite difference model is utilized to determine the thermal energy generation potential of the BIPV/T system, and to establish a relationship between electricity and useful heat generation. The gable roof with a tilt angle of 45° is used in the model. The model is applied for the design days as well as to selected sunny days representing each month of the year. The model is applied to roofs with different tilt angles, ranging from 30° to 60°, at 5° intervals. Environmental parameters including outside temperature, solar radiation, wind speed and sky temperature are provided by the weather data files of EnergyPlus.

The BIPV/T system is divided into five control volumes along the direction of the main ridge. Figure 1b depicts the thermal network of one control volume of the BIPV/T system. The various thermal conductances including that associated with the air flow (MC_{air}) are presented in Figure 1b. The PV panels are assumed to have negligible resistance and thermal capacity (Liao et al, 2007). The bottom surface of the air cavity is assumed to be well insulated.

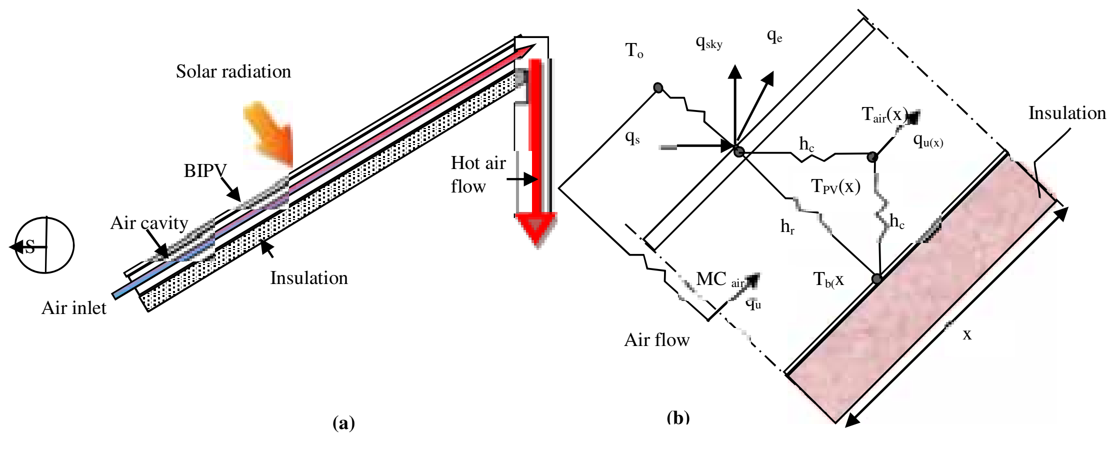


Figure 1, a) Cross-section illustrating an open loop BIPV/T system , b) schematic illustrating the thermal network in one control volume of the BIPV/T system (refer to eqs. 1-6 for meanings of symbols).

The governing equation used to describe the explicit finite difference method for a thermal network, corresponding to a node *i* and time interval *p*, is expressed by Athienitis (1998):

$$T_{(i,p+1)} = \frac{q_i + \sum_j (U_{(i,j)} T_{(j,p)})}{\sum_j (U_{(i,j)})} \quad \text{(eq. 1)}$$

where T is the temperature of a node at a specific time, q_i is the heat source at the node in question, j describes the adjacent nodes, and $R_{(i,\,j)}$ is the resistance between nodes i and j.

The air temperature (T_{air}) of each control volume is computed using equation 2 (Charron et al 2006).

$$T_{air}(x) = \frac{T_{pv} + T_b}{2} + \left(T_{in} - \frac{Tpv+Tb}{2}\right).e^{\frac{x.2}{a}} \quad \text{(eq. 2)}$$

Where, T_{pv} is the temperature of the PV panel, T_b is the temperature at the bottom side of the cavity, T_{in} is the inlet air temperature of each section (the outlet air temperature of the previous section), x is the length of the studied section, and

$$a = \frac{M.C_{air}}{W.h_c} \quad \text{(eq. 3)}$$

where M is the mass flow rate of air, C_{air} is the specific heat of air, W is the cavity width, h_c is the convective heat transfer coefficient in the cavity.

The outlet air temperature (T_{outlet}) of one section is used as the inlet air temperature (T_{in}) for the following section. The outlet air temperature at each section is determined as:

$$T_{outlet} = T_{in} + \frac{Q_u}{M.C_{air}} \quad \text{(eq. 4)}$$

Q_u is the heat carried by the air flow and is determined at each section as:

$$Q_u = A_S \,.\, [h_c(T_{pv} - T_{air}) + h_c(T_b - T_{air})] \quad \text{(eq. 5)}$$

Where A_s is the area of each BIPV/T section.

The electrical efficiency of the BIPV (η_{PV}) system is computed using the following linear equation (Florschuetz, 1979):

$$\eta_{pv} = \eta_{STC}(1 - \beta(T_{pv} - T_{STC}) \quad \text{(eq. 6)}$$

where η_{STC} is the efficiency of the PV cells under standard test conditions (STC), β is the PV module temperature coefficient, and T_{STC} is the standard test condition temperature (25ºC). A value of 12.5% is assumed for η_{STC}.

The electrical energy is determined as function of the efficiency and the solar radiation as follows:

$$Q_{e=}\eta_{pv}.\,A.\,G \quad \text{(eq.7)}$$

where (η_{PV}) is the PV efficiency (Eq.6), A is the surface area of the roof and G is the solar radiation.

The thermal energy generated by the BIPV/T Q_u can be expressed as follows:

$$Q_{u=}\eta_{thermal}.\,A.\,G \quad \text{(eq. 8)}$$

An approximate model is used to determine the thermal energy generated as a ratio of the electrical energy. From equations 7 and 8, the thermal efficiency can be determined as:

$$\eta_{thermal=}\frac{Q_u}{Qe}\cdot\eta_{pv} \quad \text{(eq. 9)}$$

The method employed to determine the ratio (Qu/Qe), between the electrical and thermal energy is based on the assumption of a constant flow in the BIPV/T system selected to ensure high efficiency. A fixed air velocity of 2 m/s is employed. This air velocity is selected as representing a commonly used value in BIPV/T applications (Athienitis et al. 2011). The present paper explores solar potential; therefore such an approach is acceptable. In practice, for design purposes a more detailed model would be advisable.

The correlation between thermal and electrical output is developed for several representative clear days of the year, as well as for several roof slopes. The correlations can be used to determine the thermal energy as well as the outlet air temperature of BIPV/T systems of different complex roof designs used in this study.

3.2. Presentation and Analysis of Results

The results of the simulations for selected sunny days, of each month of the year for a 45° tilt angle are presented in Figure 2a. Figure 2b presents the results of the simulations of the BIPV/T systems with various tilt angles, for the (WDD).

The results indicate that the ratio of solar thermal production to the electricity production (Q_u/Q_e) varies between 3 and 3.5 (mean value of 3.1 and standard deviation of 0.2). Therefore, on average, a value of $Q_u=3Q_e$ is adopted for an air speed of 2m/s in the BIPV/T system.

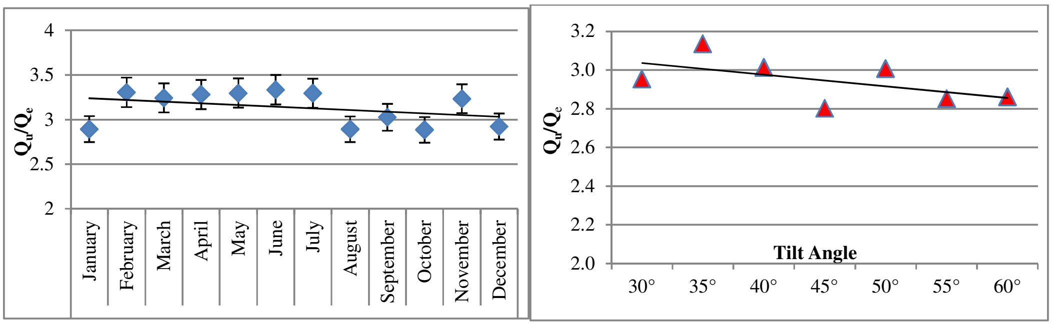


Figure 2, a) *Qu/Qe* for 45° tilt angle roof over a year, b) *Qu/Qe* for WDD of roofs with different tilt angles

4. Effect of tilt and orientation of roof surface

4.1. Approach

This section investigates the effect of tilt and orientation angles on the energy performance of the BIPV/T system of 1m^2 of roof south facing surface. Tilt angle of a surface can be defined as the angle between the normal to this surface and the normal to its horizontal projection. The orientation angle of a surface can be defined as the angle between south and the projection on a horizontal plane of the normal to this surface.

The main variables used to assess performance are the annual electricity generation, the heat production during a heating period, assumed from October 15 to April 15, and the total combined energy production. It should be noted that heat generation can be employed for water heating and for various appliances, resulting in an increase of the overall potential use of the output of the BIPV/T system year round. EnergyPlus is used to simulate the response of combinations of tilt angle ranging between 30° and 60°, and orientation ranging between 60° east and 60° west of south. A simple program is developed, using *Matlab* program, to generate the input files for EnergyPlus.

4.2. Presentation of results

Tilt angle

The annual electricity generation of the BIPV/T system is not significantly affected by a tilt angle that ranges between 30° and 50°. The heat generation for the period between mid-October and mid-April is reduced by approximately 4% for the tilt angle of 30°, as compared to the 45° tilt angle. For a 60° tilt angle, the annual electricity production is reduced by some 7% as compared to the 45° tilt angle, while the heat generation for the assumed heating period is reduced by only 2%. For a winter design day, tilt angle of 60° can produce up to 8% more electricity than 45° tilt angle. For the SDD a tilt angle of 30° yields 11 % more electricity than the 45 ° tilt angle. In general, high slope roofs (>40°) are favored in climates such as those in most of Canada due to the snow accumulation factor; however, this factor is not considered directly in this study.

Orientation

The effect of the orientation on electricity generation, for the design days and the total year generation associated with a 45° tilt angle BIPV/T system is presented in Figure 3a. The effect is measured as the ratio to the generation of a south facing BIPV/T system (orientation = 0). Annually, the highest energy yield is associated with a south facing system. Deviation of the orientation of the system from the south by up to 40° west or east leads to an approximate reduction of 5% of the annual generation of electricity (Fig. 3a). The heat generation for the assumed heating period is reduced by up to 9%, for the orientation angle of 40° west or east (Fig. 3b). A rotation of the system by 60°, west or east of south, results in a reduction of some 12% of the total annual electricity generation and of 20% of the heat generation during the heating period.

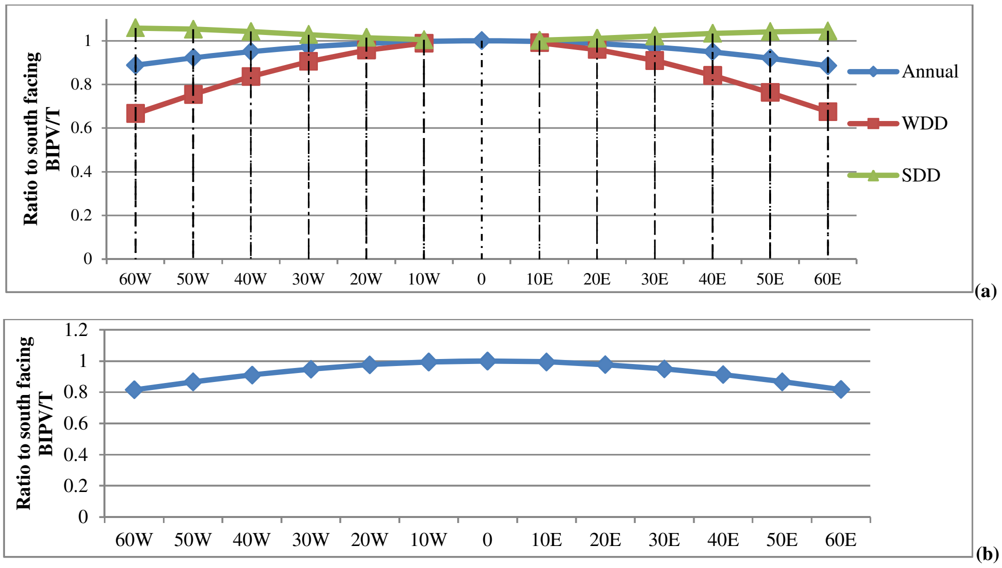
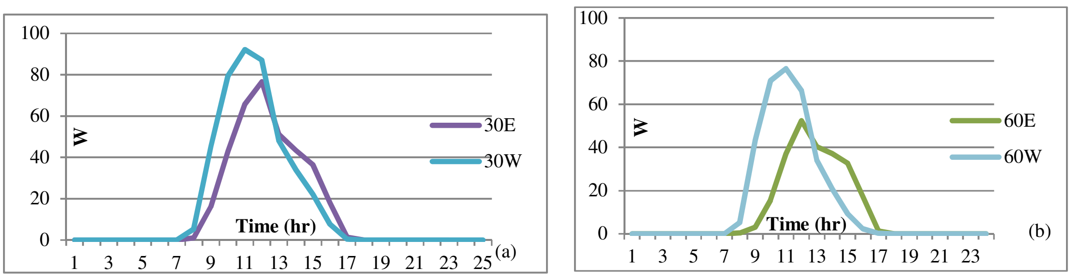


Figure 3, Effect of the angle of orientation on: (a) the electricity generation, (b) heat generation accumulated over the period between mid-October and mid-April.

The orientation of the BIPV/T system affects not only the value of the electricity generation, but also the time of peak generation. For a south facing system, the peak generation is at noon. Rotation of the BIPV/T system towards the west results in shifting the peak radiation to the afternoon and vice versa for east rotation. A 30° orientation (east or west), enables a shift of peak generation time to up to 2 hours relative to solar noon. A 60° orientation enables a 3 hours shift of peak. Roofs that combine both east and west orientations can lead to a spread of peak generation time, reaching six hours.

In some cases, return on annual energy produced may be a more important object than the total energy produced, particularly in locations where prices of electricity vary with time of day. For a net-zero energy house or community the annual net income becomes an important variable to optimize as the value of the electricity produced may be higher than that consumed. This involves consideration of orienting the BIPV/T systems to obtain peaks at the time of high electricity demands, enabling thus larger annual income from selling the excess electricity to the grid.

These results are illustrated in the charts of Figure 4, for the WDD and SDD.



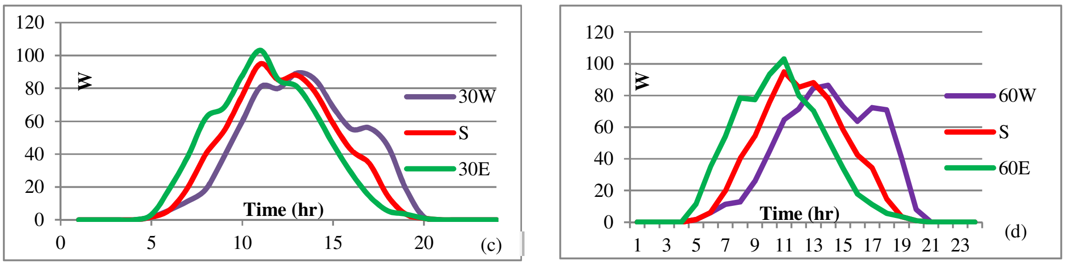


Figure 4, Effect of the angle of orientation on the electricity generation, (a) 30° for the WDD, (b) 60° for the WDD, (c) 30° for the SDD, (d) 60° for the SDD

Combination of tilt and orientation angles

The yearly study shows that for the winter months between September and March, the most effective BIPV/T systems are those that combine a tilt angle of 45° to 60° together with a south facing orientation. These configurations allow the highest yield of electricity generation as well as heating energy. In the summer months, lower tilt angles and rotation, particularly west, are advantageous. The annual electricity generation, the heat generation for the heated period and the combined energy generation are presented in Table 1, for different combinations of tilt and orientation angles. The comparison of the results of all these combinations to a south facing BIPV/T system with 45° tilt angle is presented in Figure 5.

Table 1: Electricity generation, heat generation and combined generation of various combinations

Orientation	Tilt								
	30°			45°			60°		
	Yearly electricity Generation (kWh)	Heat generation (heating Period) (kWh)	Combined generation (kWh)	Yearly electricity generation (kWh)	Heat generation (heating Period) (kWh)	Combined generation (kWh)	Yearly electricity generation (kWh)	Heat generation (heating Period) (kWh)	Combined generation (kWh)
30W	192.64	280.61	473.25	189.51	288.07	477.58	181.27	297.19	478.47
30E	192.48	281.12	473.60	189.31	288.69	478.00	176.11	279.15	455.26
South	197.28	292.45	489.73	194.90	303.78	498.68	175.96	279.97	455.93
60W	179.10	249.76	428.87	173.12	247.88	421.00	159.56	234.24	393.80
60E	178.86	250.73	429.58	172.59	248.53	421.12	159.37	235.75	395.11

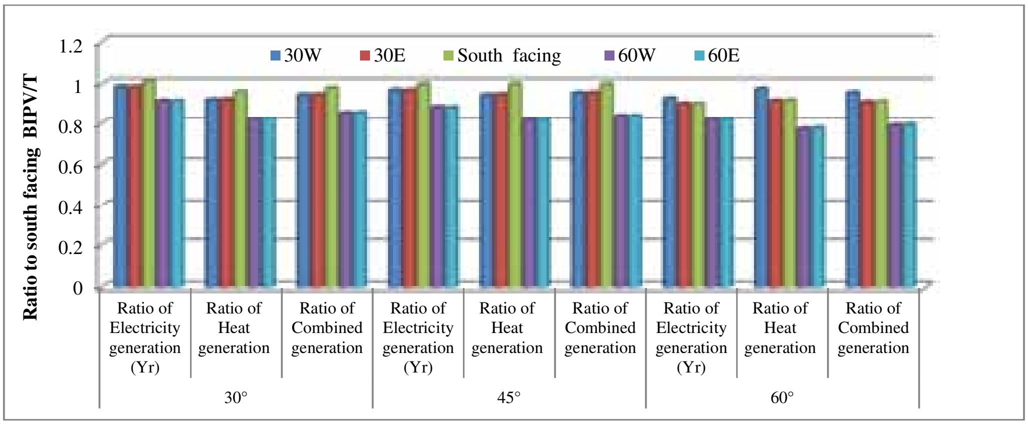


Figure 5. Ratio of energy generation of different configurations (combining tilt and orientation angles) to south facing BIPV/T system with 45 ° tilt angle

5. Application to roof design of a rectangular unit

5.1. Roof design

This part of the study, explores various design possibilities of roof shapes for a rectangular house, to maximize solar energy potential. The rectangular house has 60 m^2 floor area (per storey), and an aspect ratio of 1.3. The aspect ratio is the ratio of the south facing façade to the perpendicular façade. This ratio is considered optimal for passive solar design in northern climate (Athienitis and Santamouris 2002).

Three basic geometries of roofs are studied. The first geometry is a commonly used roof-hip roof with varying side angles (Fig. 6). The second and third types of roofs are designed relatively independently of the shape of the house, employing a multi-faceted roof surface combining a range of tilt and orientation angles.

Hip roof design

The hip roof is designed with the ridge running east-west (E-W) at the center of the plan area (Fig .6). Three side angles are used: 45°, 60°, and 90°. The side angle is the angle between the plane ABC and the horizontal plane, as shown in Figure 6. The tilt angle is kept constant at 45°. Tilt angle is in this case the angle between the normal to BCDF (Fig.6) and the normal to its horizontal projection. BIPV/T system is assumed to cover the total south facing surface of the roof.

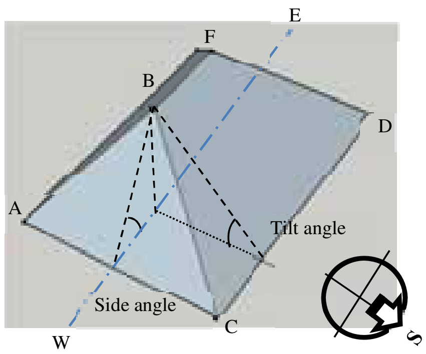


Figure 6, hip roof design

Tri-plate roof

This concept divides the south-facing portion of the roof into three plates of differing orientations and tilt angles. A BIPV/T system is assumed to cover the total area of each of these plates.

Two main configurations are considered, as well as some variations of these options. The mid plate is south oriented while the side plates are rotated by equal angles, the east plate towards the east and the west plate towards the west. In the first option, the orientation angle of the side plates is 15°, while in the second option this angle is 30°. The orientation angle, as defined above, is the angle between south and the projection on a horizontal plane of the normal to the surface (e.g. *ABCD* in Fig.7b).

For each of the two configurations, a few variations of tilt angles are used to explore the effect on the overall solar potential of the roof. The two configurations of the plate roofs are presented in Figure 7 and the details of the combinations are included in Table 2.

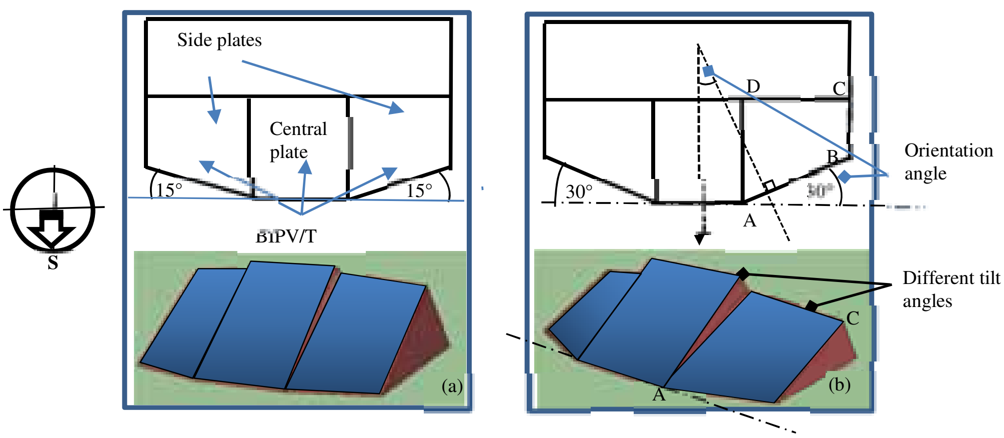


Figure 7, tri-plates roof designs: (a) configuration 1, side plates with 15° orientation from south; (b) configuration 2, side plates with 30° orientation from south

Folded plate roofs

Folded plate roof design refers in this paper to the shape of the roof, not necessarily to the structural system. The folded plate roof design is composed of triangular plates with various orientations. Two basic shapes are designed. The first configuration is composed of 4 plates, with the two side plates facing south (see Fig. 8a). The second basic shape consists of three plates with the central plate facing south (Fig. 8c shows a variation of this shape composed of two basic units).

Variations of the basic shapes are composed of two, and possibly more, units of the basic shape. Figure 8 presents the three configurations analyzed in this study. The first configuration (Fig. 8a) is the 4-plate basic shape, with the central plates rotated 15° east and west and the side plates having 45° tilt angle. The second configuration (Fig. 8b) is composed of two basic 4-plate units, with central plates rotated 30° east and west. The third configuration (Fig. 8c) is composed of two 3-plate basic shapes with side-plates rotated 30° east and west. Details of the folded plates' configurations are presented in Table 2. Effect of these roof desings on the energy performance of the housing units is an ongoing research.

The BIPV/T system is assumed to cover the total area of south and near south facing triangular plates. Technical considerations of how to apply PV cells on triangular plates, are not addressed in this research and should be taken into account in future research for the actual applications of these roof systems. Future technical considerations include the need of different inverters for different BIPV/T orientations.

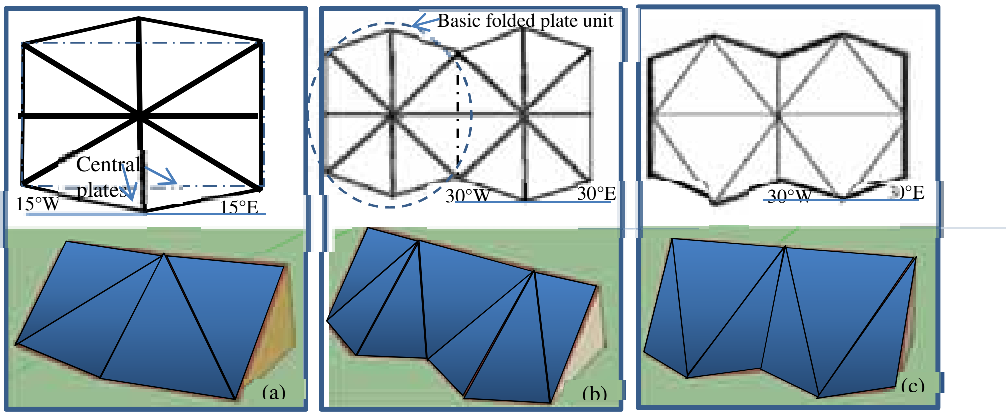


Figure 8, folded plate roof designs, (a) configuration 1-- basic 4 folded plates with 15 °orientation;, (b) Configuration 2 -- two basic folded plates units with 30° orientation, (c) Configuration 3 -- six folded plates roof with 30 ° orientation

Table 2, design consideration Tri-plates 'roofs and folded plates' roofs

Complex roof	Side angle	Number of surfaces	Combinations of orientation and tilt of the plates*				
Tri-plates	90°	3	Configuration 1	Center plate	0°, 45°;	0°, 50°;	0°, 45°;
				Side plates	15°(E,W), 40°	15° (E,W), 40°	15° (E,W), 30°
			Configuration 2	Center plate	0°, 45;	0°, 50°;	0°, 45°;
				Side plates	30°(E,W), 40°	30° (E,W), 40°	30° (E,W), 30°
Folded plates	90°	4 - (Basic folded plates)	Configuration 1	Center plate	0°, 45°;		
				Side plates	15° (E, W)		
		7(2 basic folded plates)	Configuration 2	Center plate	0°, 45°;		
				Side plates	30° (E, W)		
		6 (two 3-plate basic shapes)	Configuration 2	Center plate	0°, 45°;		
				Side plates	30° (E, W)		

*The first number refers to the orientation and the second number refers to the tilt angle;

5.2. Simulation results

Simulations using EnergyPlus were performed to determine the energy generation potential of all roof shapes presented above. The correlation between the electrical and thermal energy generation of the BIPV/T system, derived in the first stage of the investigation is applied to determine the thermal energy potential of the roofs. Results are presented for the electricity generation annually and for the winter and summer design days. Heat genertion results are over the assumed heating period (mid-October to mid-April) and for the winter design day. The combined annual electricity and winter heating energy production are also presented. The main observations drawn from the analysis of all roof designs are summarized below.

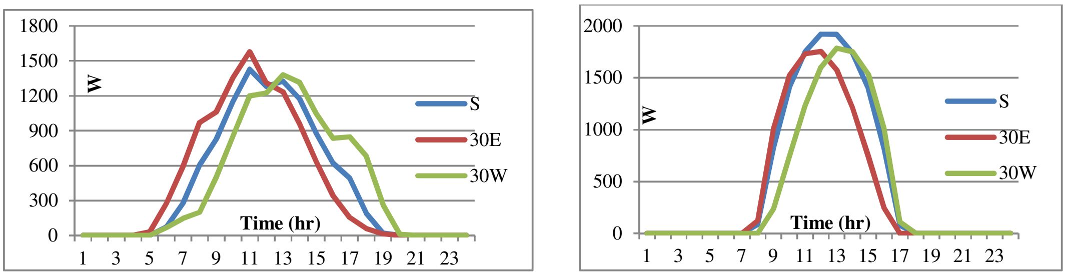
- The side angle in the hip roof design, affects mainly the south facing roof area. The largest south roof area is obtained with the larger side angle (90°) corresponding to a gable roof (Fig. 6). The electricity and heat generation of a hip roof with a 45° side angle is reduced by approximately 40% as compared to the gable roof. The comparison between different roofs and the gable roof are presented in Table 3.
- The tri-plate roof design has two main characteristics: it enables larger south facing roof area (about 48 m^2) as compared to the gable roof ($40m^2$) and it facilitates combinations of orientation and tilt angles, which allows obtaining spread of peak generation time of up to 3 hours, (Fig.9). The results (table 4) indicate that there is no significant change of the energy potential between the different combinations, of configuration 1 and 2 (3% or less). A significant increase in the annual energy production is however obtained using this roof design, as compared to the gable roof. For instance, configuration 1 (with 15° orientation) exceeds annual electricity generation of the gable roof by 17% and heat generation for the assumed heating period by 15%. The annual electricity generation, the heat generation for the heating period and the combined energy potential, are presented in Table 4. The potential heat generation on the WDD and the average air temperature difference (ΔT) are also presented in Table 4.
- Folded plate roof design enables obtaining various orientations for the same rectangular plan roof. Furthermore, this roof shape has significantly higher south facing surface area than the gable roof (see Table 3). The different configurations analyzed in this paper do not show a significant difference in their solar potential (maximum difference of 4% is observed). The roof options with 15° orientation allows a spread of time of peak generation of approximately 2 hours while the 30° enables 3 hours difference. The six plate folded roof (Fig. 8c) electricity generation exceeds the generation of the gable roof by approximately 30% (Table 4). The solar potential of these roof options are presented in Table 4.

Table 3, comparison of all roof design options to the gable roof

	Hip side angle			Tri-plates		Folded Plates		
	45°	60°	90°	15°(E,W),40°	30°(E,W),40°	Conf. 1 (15)	Conf. 2 (30)	Conf. 3 (30)
South facing roof Area	26	32	40	48	48	50	53	53
Comparison of electricity generation to Gable roof	0.65	0.81	1	1.17	1.15	1.25	1.27	1.29

Table4, Results of the energy potential of the multi-faceted roof design options

Roof Options		Annual Electricity generation (kWh)	Heat generation (heating Period) (kWh)	Combined generation (kWh)	Electricity generation WDD (kWh)	Electricity generation SDD (kWh)	Heat generation (WDD) (kWh)	Average air change temperature ΔT (WDD)(°C)
Gable roof		7560.9	10068.3	17629.2	29.6	18.8	88861.6	10
Tri-plates	15°(E,W),40°	8814.6	11543.9	20358.5	33.6	22.3	101	9.5
	30°(E,W), 40°	8636.4	11169.4	19805.7	32	22.4	100	9
Folded Plates	Conf. 1 (15)	9460.3	12707.9	22168.1	37.6	23	113	10.2
	Conf. 2 (30)	9635.6	12974.2	22716.9	38	23.8	114.3	9.7
	Conf. 3 (30)	9743.0	12850.9	22486.5	38.2	24.3	115	9.7



(a) (b)

Figure 9, Electricity generation on design days for the west and east oriented plates in the 30°(E,W), 40° roof option, (a) SDD, (b) WDD.

Conclusion

A study aimed at enhancing roof design for utilization of energy potential by BIPV/T systems is presented in this paper. The study investigates the design of roof shapes of two-story rectangular housing units located in Canada – mid-latitude northern hemisphere.

A correlation is established between electricity and heat generation of an open loop air-based BIPV/T system. Analysis for different days and different roof tilt angles produces an almost constant ratio of heat-to-electrical energy production of 3, under a fixed air fan speed of 2m/s. This correlation provides a simple tool for computing thermal energy production based on electricity generation obtained by simulation.

Advanced roof design enables control of orientation and tilt angle of roof surfaces. Both the orientation and tilt angle of the BIPV/T system affect its overall energy generation. The annual electricity generation of the BIPV/T system is not significantly affected by a tilt angle that ranges between 30° and 50°. The yearly electricity generation is reduced by approximately 12% with an orientation of 60° east or west from south, while the heat generation for heating months (15 October-15 April) is reduced by ca 20%. The orientation of a roof affects as well the time of peak generation. This can be of particular advantage in cases where the value of electricity varies with the time of day.

Multi-faceted roofs, such as folded plate and split-plate configuration, can significantly increase electricity production and heat generation (over an assumed heating period), primarily through increased effective surface area. Dividing the reference gable shaped roof surface into three plates with varying tilt/orientation angles can increase electricity generation by up to 17%. Replacing the gable roof with a folded plate surface increases electricity generation by up to 30%. Varying surface orientations in such roof designs enables spread of peak electricity generation by up to 3 hours.

The significance of this study lies in highlighting the role of roofs morphology in increasing the overall solar energy generated, as compared to a regular hip/gable roof, as well as enabling spread of different peak electricity generation time. The application of such roofs in a housing assembly can be beneficial for both the owners and the grid utility.

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