Potential energy savings from a semi-transparent solar cell window system for code-compliant residential buildings in hot and humid climates

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Abstract

A semi-transparent solar cell window system is one of the most recent building integrated PV window technologies (i.e., BIPV window). This type of BIPV window systems can generate photovoltaic electric energy and can be designed to admit a specific amount of natural light and/or view to an indoor space. This study evaluates potential energy benefits of integrate semi-transparent solar cell windows on a 2009 International Energy Conservation Code (IECC) code-compliant residential building in a hot and humid climate. The energy analysis is based on a whole-building simulation model with a DOE-2.1e, which include a BIPV window module specially made for this study. The study analyzed peak demand, energy use, and electricity production from each orientation (east-, west-, south-, and north-facing). As a result, the south-facing window showed the greatest potential to generate electric power and to reduce building loads and system energy use. In comparison to the code-compliant base-case model, the BIPV windows provided noticeable energy savings about 12-21% in annual site energy use.

Keywords: *Building integrated PV, Energy simulation, Residential building, International Energy Conservation Code, DOE-2.1e simulation program*

1. Introduction

Hot and humid climates demand significant electricity for cooling. In 2001, Texas implemented the Texas Emissions Reduction Plan (TERP) program that aims to diminish the pollution in the state by energy efficiency and renewable energy measures. To lower pollution to generate electricity from fossil fuels, Texas has been utilizing applications of renewable energy resources for both power plants and buildings.

As one of the efforts to reduce pollution, Texas has built renewable energy plants to generate electricity from eco-friendly fuel resources (e.g., mainly wind, solar, and biomass) (Haberl et al., 2014). Texas is one of the largest renewable energy producers in the United States (US), leading the nation in wind-powered generation capacity with over 14,000 megawatts (EIA, 2015; Haberl et al., 2015).

In addition to these efforts, other renewable energy applications to buildings (e.g., photovoltaic, PV, technology integrated into buildings) have been used to reduce the building's energy demands due to onsite power generation, and it resulted in reducing energy demands on power plant (Haberl et al., 2014; NREL, 2015). Recently, an interest in a semi-transparent solar cell window system (i.e., a building integrated photovoltaic (BIPV) window) has increased worldwide (bccResearch, 2011; DOE, 2015b; Kang et al., 2013; Sivanandan, 2009; SNE, 2011) because the these solar cell windows generate electricity without constructing additional PV structures on a building envelop and also provide natural light transmission (Kang et al., 2013; Lee et al., 2014; Li et al., 2009; Yoon et al., 2011). Due to these features, building designers and engineers may use the BIPV windows to generate electricity and to create unique daylighting features in building façades (e.g., window and sunroof), which at the same time reduce unwanted cooling load and glare associated with architectural glazing (Li et al., 2009).

In the US, a new residential construction must comply with a residential building energy code for its energy certificate. A number of residential building energy codes and standards (e.g., IECC, ASHRAE Standard 90.2, California Title 24, etc.) have been developed and adopted. In the US residential sector, the IECC is widely adopted as the state energy code in approximately 40 of the 50 US states (DOE, 2015c). Since January 2012, Texas has adopted the 2009 IECC (ICC, 2009) even though newer versions of IECC (i.e., 2012 and 2015 IECC) are available (DOE, 2015a; SECO, 2015). The aim of this study is to evaluate the potential effects of implementing semi-transparent solar cell windows on a residential building that complies with the adopted state energy conservation code (i.e., 2009 IECC) and is located in a hot and humid climate.

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2. Semi-transparent solar cell windows

A semi-transparent solar cell window system (BIPV window) is one of many of the PV technology applications to buildings. The BIPV window system can generate photovoltaic electric energy, and can be designed to admit a specific amount of natural light and/or view to an indoor space (Yoon et al., 2011; DOE, 2015a, 2015c; SECO, 2015). In comparison to the conventional PV cells, it has several advantages: ease-to-manufacture due to no need for vacuum processes, capability to be colorable and transparent, applicability to flexible thin structure, and light weight (Miyazaki et al., 2005).

To calculate the electricity generation from the BIPV window, the PV efficiency (η) is determined as the fraction between the maximum power which a solar cell can convert from absorbed light to electrical energy (P_{max}) and the incident power (P_{in}). This study used Eq. (1) and Eq. (2) for the efficiency calculation, which are basic solar cell efficiency equations (Duffie and Beckman, 2013; Servaites et al., 2009; Sze and Ng, 2006). The degradation of the solar cell efficiency due to the increased cell temperature in operation was not considered in this study.

$$FF = \frac{V_{MP} \cdot I_{MP}}{V_{OC} \cdot I_{SC}} \qquad \text{(eq. 1)}$$

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{MP} \cdot I_{MP}}{P_{in}} = \frac{V_{OC} \cdot I_{SC} \cdot FF}{P_{in}} \qquad \text{(eq. 2)}$$

where P_{max} is the maximum power (W), FF is the fill factor to determines the maximum power from a solar cell, V_{MP} is the maximum power voltage (V), I_{MP} is the maximum power current (A), V_{OC} is the open-circuit voltage (V), I_{SC} is the short-circuit current (A), η is the PV efficiency, and P_{in} is the incident power (W), which is based on 1 kW m^{-2} for the efficiency calculations. The BIPV window electric power generation is estimate using Eq. (3) (Chae et al., 2014; Corrao and Morini, 2012; Duffie and Beckman, 2013; Servaites et al., 2009; Sze and Ng, 2006).

$$P = \eta \cdot A \cdot G \qquad \text{(eq. 3)}$$

where P is the generated electricity from a BIPV window (W), A is the BIPV window surface area (m^2), and G is the global irradiance on a BIPV window surface (W m^{-2}).

3. Semi-transparent solar cell windows

To evaluate the potential energy benefits from implementing the BIPV windows instead of conventional windows, this study simulates a 2009 IECC code-compliant residential building. The simulations are conducted under a hot and humid climate; this study selects the city of Houston, the Climate Zone 2 classified in IECC. The overall research methodology is briefly presented in Fig. 1.

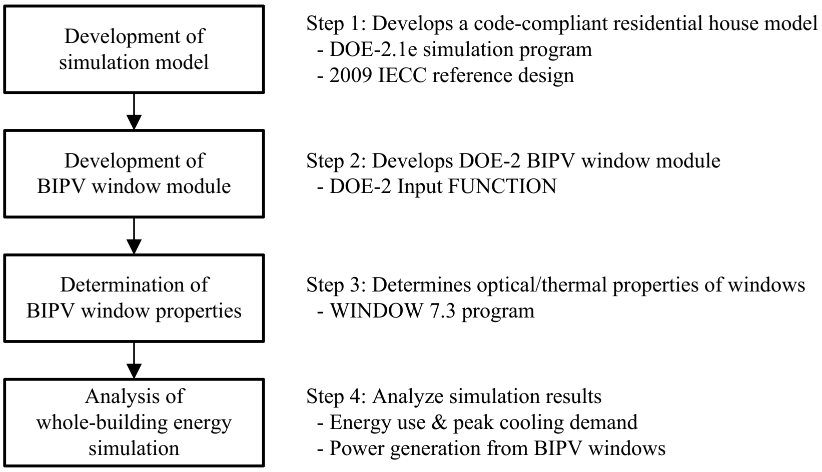


Fig. 1: Diagram of overall research methodology

In order to develop a code-compliant residential base-case simulation model, the requirements as defined in Chapter 4 of the 2009 IECC were referenced (ICC, 2009); the input parameter values such as envelope insulation, window area, and system efficiency were determined according to the code requirements (Do and Haberl, 2015). The developed base-case model (see Fig. 2) had a simplified structure with a rectangular geometry, flat roof, and no attic space; they are a single-story, single-family, south-facing and detached house that has 232 m^2 of floor area and a 2.4 m floor-to-ceiling height without a plenum. For this study, the base-case model was modified to have five interior thermal zones, including east, west, south, north, and core. The base-case model used a double-pane window with a bronze-tinted glass. The window area on each exterior wall was determined using a 15% window-to-floor ratio (WFR), which was equivalent to a 23.4% window-to-wall ratio (WWR) for the base-case. In addition, this study used the Residential System (RESYS) in the DOE-2.1e program (DOE2, 2015) for a typical residential air-source heat pump system. The simulations for this study were performed using Typical Meteorological Year version 3 (TMY3) weather file.

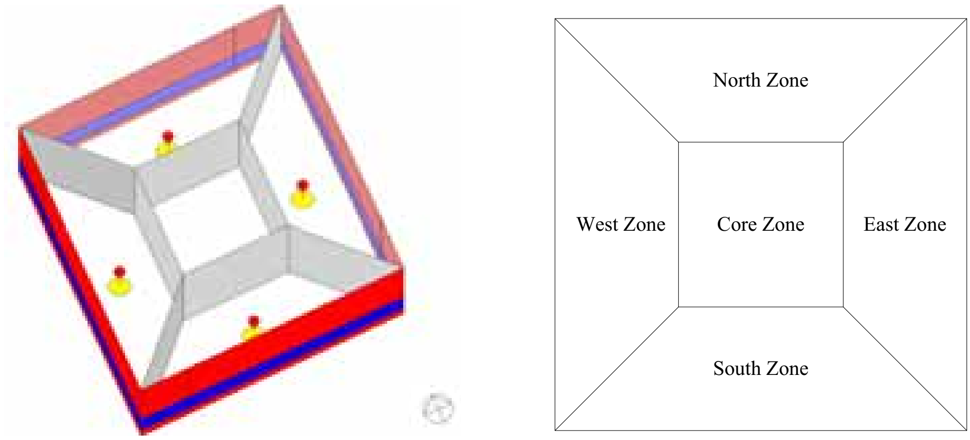


Fig. 2 (a)

Fig. 2 (b)

Fig. 2: View of the base-case simulation model: (a) exterior 3D view; and (b) interior thermal zoning

In order to calculate the electricity power generated from BIPV windows on each exterior wall, the BIPV window module was developed using the DOE-2 input FUNCTION commands, which can be written in the Building Description Language (BDL) input file without debugging the DOE-2.1e program (LBL, 1993). The BIPV input FUNCTION commands collects the incident solar radiation on each outside window surface for each hour of the run period, and calculates hourly electric power generation from each BIPV window. The results of the calculated hourly electricity generation are separately saved as an output file.

In order to add the calculation of the BIPV window power generation into the DOE-2.1e calculation algorithm, the BIPV input FUNCTION commands were written in the LOADS section of the input BDL file. This study selected three types of the BIPV transparency: 40%, 20%, and 10%. The electrical performances of the selected BIPV types were obtained from the published data (Episolar, 2015). Table 1 presents the BIPV properties for the electrical performances.

Table 1. Electrical performance properties of the selected BIPVs

BIPV	Transparency (%)	Nominal Power (W)	Voc (V)	Isc (A)	Vmp (V)	Imp (A)	Pin (W)	Fill Factor -	Efficiency (%)
Type I	40	48	116	0.59	87	0.55	720	0.6992	6.65
Type II	20	64	116	0.78	87	0.73	720	0.7019	8.82
Type III	10	72	116	0.88	87	0.82	720	0.6989	9.91

The base-case window had a double-pane unit consisting of two layers of glasses, and the two layers were separated by an air gap. To evaluate the thermal performance of the window glass, three glass properties are required as the simulation input parameters: glass conductance (i.e., U-factor), shading coefficient (SC), and visible transmittance (T_{vis}). These input parameters were estimated using the WINDOW 7.3 program which is a windows and daylighting software developed by Lawrence Berkeley National Laboratory (LBNL) (LBNL, 2015). Using the glass library data in the WINDOW 7.3 program, the thermal and optical properties of the glasses used for the base-case and BIPV windows were determined. Table 2 presents the details of the window input parameter values used for performing DOE-2.1e building energy simulations.

Table 2. Defined window input parameters for simulations

DOE-2 Input Parameters	Base-Case	BIPV Type I	BIPV TYPE II	BIPV Type III	Note
GLASS-CONDUCTANCE (W/m^{2}K)	2.699	2.603	2.412	2.308	Glass conductance
SHADING-COEF	0.574	0.422	0.253	0.182	Shading coefficient
VIS-TRANS	0.468	0.359	0.183	0.091	Visible transmittance

To implement a daylight-dimming system in simulations, this study used the existing daylighting calculation in DOE-2.1e. One reference point at which daylight illuminance levels were to be calculated was used for each exterior thermal zone (i.e., east, west, south, and north zones); it was assumed that a photocell controls the electric lighting system that responds to the light levels at the specified reference point. In simulations, the desired minimum lighting level (i.e., illuminance set point) was defined as 323 lux (30 fc), assuming a general ambient lighting level for a residential building. The lighting reference point was located at the middle of each space with 0.8 m (2.5 ft) height.

4. Semi-transparent solar cell windows

4.1. Power generation from BIPV windows

The electricity power generated from the BIPV window on each exterior wall was evaluated using the developed BIPV window module. Fig. 3 presents the estimation of the electric power generation from the BIPV Type II windows for different orientations.

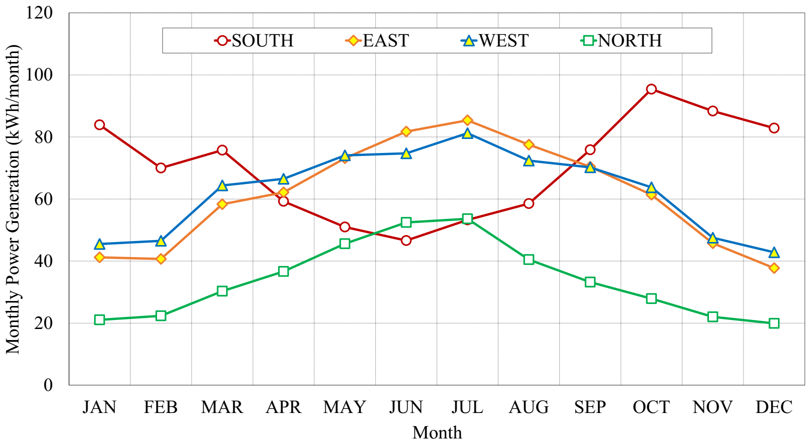


Fig. 3 (a)

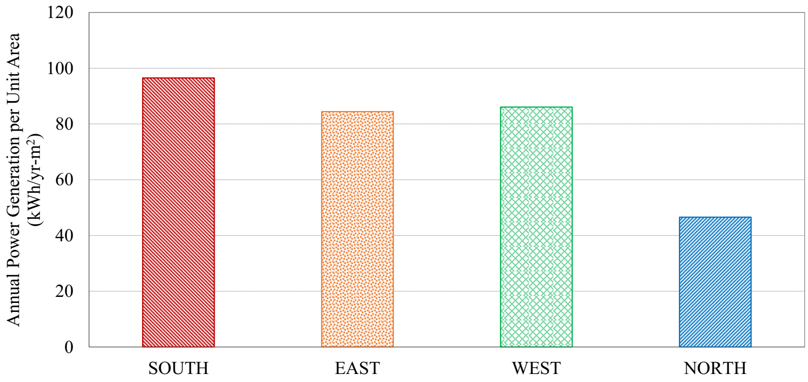


Fig. 3 (b)

Fig. 3: Electric power generation from BIPV II for different orientations: (a) monthly total; and (b) annual average power generation intensity

In general, the largest annual power generation was observed in the south-facing BIPV window whereas the smallest annual power generation was observed in the north-facing BIPV window. The east- and west-facing BIPV windows resulted in the similar amount of power generation. In addition, the east-, west-, and north-facing

BIPV windows generated more power during the summer period (May through August) than the winter period due to larger solar radiation and longer sunshine hours. On the other hand, the south-facing BIPV window generated less power during the summer period (especially in June) than the other periods due to the relation between the sun angle at a given time/location and a 90° exterior wall. That is, the projected area of the south-facing window during the summer period was relatively small to absorb solar radiation.

4.2. Building loads

The simulation results showed that the implementation of the BIPV window provided benefits in the annual building load reductions in comparison with the baseline case. This reductions came from the BIPV thermal performance that decreased shading coefficient in comparison with the base-case window (see Table 2). Fig. 4 presents the estimated distribution of the total annual building loads reduction from the implementation of the BIPV Type II windows in each of the orientations. The largest reductions occurred in the south-facing space; east- and west-facing spaces resulted in the similar annual reductions; and the north-facing space had the least reductions. This indicates that a south-facing space will be the most beneficial space in annual total building loads reduction from a BIPV window at a given location with a hot and humid climate.

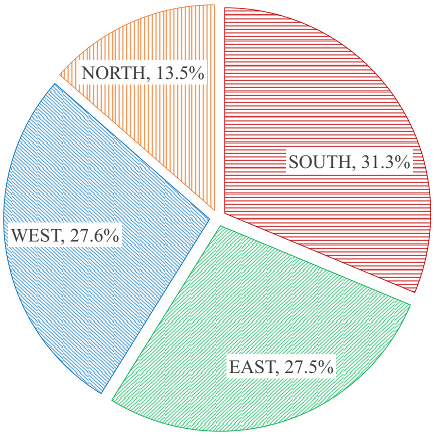
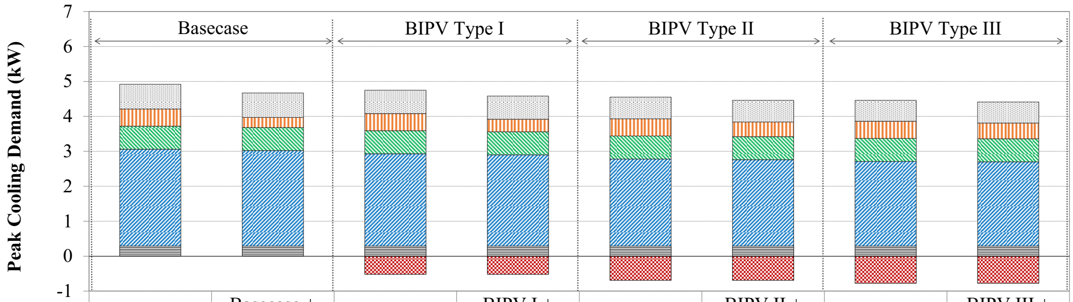


Fig. 4: Distribution of total annual building loads reductions for the implementation of BIPV type II windows according to the orientation

4.3. Cooling peak demands

The simulation results for the peak demands during the cooling season, including energy uses for cooling, lighting, others (i.e., miscellaneous equipment, heating, pumps, fan, and hot water), and for the generated BIPV power for the three BIPV types analyzed are presented below in Fig. 5.



	Basecase	Basecase + Dimming	BIPV I	BIPV I + Dimming	BIPV II	BIPV II + Dimming	BIPV III	BIPV III + Dimming
Total	4.92	4.67	4.23	4.06	3.86	3.77	3.68	3.63
░ Pumps & Fan	0.71	0.70	0.67	0.66	0.62	0.62	0.60	0.60
▥ Area Lights	0.49	0.29	0.49	0.36	0.49	0.42	0.49	0.45
▧ Misc Equipmt	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
🟥 Space Heat	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
▨ Space Cool	2.77	2.73	2.64	2.61	2.49	2.47	2.42	2.41
▤ DHW	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
▦ PV Power	0.00	0.00	-0.52	-0.52	-0.69	-0.69	-0.78	-0.78

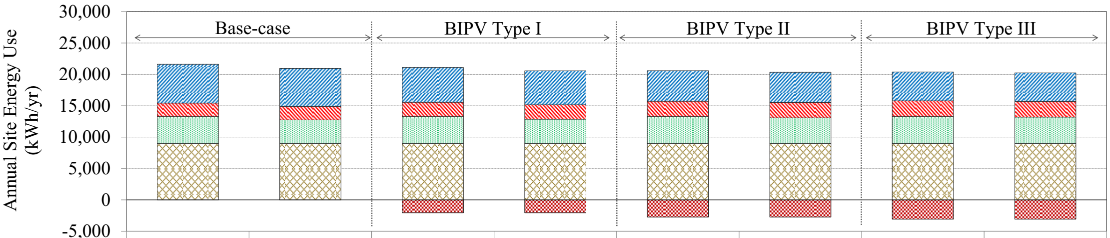
Fig. 5: Comparison of peak demands during the cooling season

The BIPV type and daylight-dimming system reduced the peak demands in a range from 14.0% (0.69 kW) to

26.1% (1.29 kW), in comparison with the baseline case. When using a daylight-dimming system integrated with the BIPV window, the savings increased in both the cooling energy and the electrical lighting energy use. In general, the system's peak demands influences the determination of the system capacity, and thus the peak demands reductions indicate that there is a possibility for the cooling system to be downsized, which provides additional energy and cost savings due to lower compressor's power consumption.

4.4. Annual site energy use

As it has been presented above, the implementation of BIPV windows and daylight-dimming system influence the building energy performance: electricity power generation, decrease supplementary lighting, decrease building cooling loads, and decrease cooling peak demands. As a consequence, the BIPV window provided energy benefits in annual energy use of the building system. Fig. 6 presents the resultant annual energy use for the three analyzed window type, including cooling, heating, lighting, others (i.e., miscellaneous equipment, pumps, and hot water), and the BIPV power generation. In addition, Fig. 6 includes percent savings from the BIPV window in comparison with the code-compliant baseline which does not include a daylight-dimming system.



	Base-case	Base-case + Dimming	BIPV I	BIPV I + Dimming	BIPV II	BIPV II + Dimming	BIPV III	BIPV III + Dimming
Total	21,617	20,966	19,046	18,522	17,861	17,615	17,314	17,191
▨ Cooling	6,186	6,060	5,541	5,425	4,862	4,820	4,585	4,550
▧ Heating	2,155	2,157	2,288	2,290	2,454	2,455	2,521	2,522
▥ Area Light	4,279	3,751	4,279	3,869	4,279	4,074	4,279	4,191
▩ Others	8,997	8,997	8,997	8,997	8,997	8,997	8,997	8,997
▩ BIPV Power	0	0	-2,059	-2,059	-2,731	-2,731	-3,069	-3,069

Fig. 6 (a)

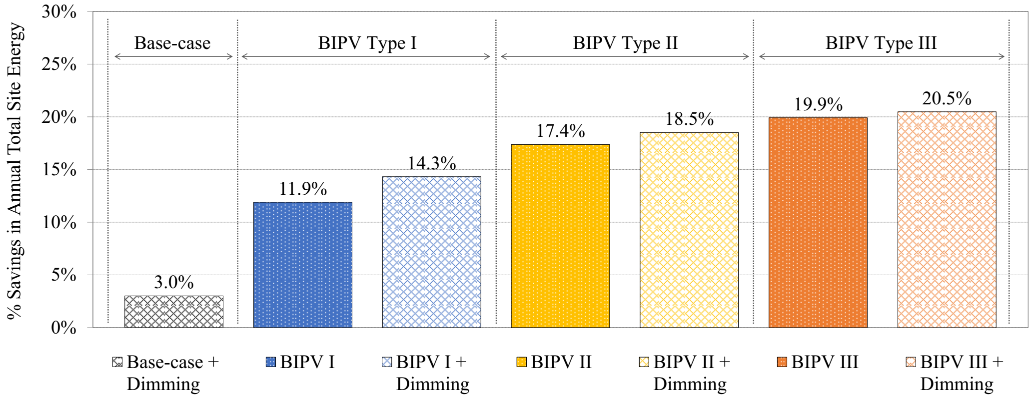


Fig. 6 (b)

Fig. 6: Comparison for annual site energy consumption: (a) annual energy use; and (b) percent savings against the base-case without a daylight-dimming system

The cooling energy use was significantly decreased with in a range from 10% (645 kWh/yr) for the BIPV type I to 26% (1,637 kWh/yr) for the BIPV type III. On the other hand, the heating energy use was increased from 6% (133 kWh/yr) for the BIPV type I to 17% (367 kWh/yr) for the BIPV type III. The increase/decrease amount of the cooling/heating energy use appeared to be caused by the BIPV window shading coefficient values (see Table 2); a low SHGC value led to a decrease in cooling energy use and an increase in heating energy use. In the simulations for a daylight-dimming system, the transparency value of the BIPV glazing appeared to influence on the electric lighting energy use; a higher transparency value resulted in bigger reduction in electric lighting energy use. Regarding the electric power generation, the higher electric power was generated from the BIPV type III because of the different BIPV's efficiency values (see Table 1).

In the calculation of the percent savings for the annual total site energy use, the generated electric power compensated the system's electricity consumption. The amount of the percent savings resulted from the BIPV window and a daylight-dimming system ranged from 11.9 to 20.5%. The BIPV type III resulted in the largest savings for the annual total site energy due to the significant cooling energy reduction and power generation. However, the daylight-dimming system using for the BIPV type III did not result in noticeable energy savings due to low transparency value. A cost analysis to evaluate economic benefits may be required to determine the optimal energy savings goals when using a daylight-dimming system for a BIPV window.

5. Summary and conclusions

To quantify the energy benefits of the BIPV window in hot and humid climates, a typical residential building was simulated in DOE-2.1e. A BIPV window module was developed for DOE 2.1e and implemented it into the 2009 IECC code-compliant residential building model. Based on the energy simulation results, potential energy benefits from utilization of the BIPV system were realized including: power generation, annual building loads, cooling peak demands, and annual total site energy use. Based on the analysis results completed in this study, the following conclusions can be made:

- The electric power generated from the BIPV window depends on its efficiency value, area, orientation, and incident solar radiation. The south-facing windows can produce the largest annual electricity, but the east- and west-facing windows present the highest potential to generate electricity during the summer period.
- Implementation of the BIPV window resulted in a reduction in the total annual building loads, ranged from 6 to 15%. In addition, the south-facing space was identified as the most beneficial space in reducing annual building loads. However, it should be noted that the BIPV power generation from the south-facing window was also reduced during the summer period when higher electricity power was consumed than the other periods. Therefore, the further study is required to optimize building loads reduction and BIPV power generation.
- The BIPV window and daylight-dimming system led to reductions in the peak cooling demands, from 14 to 26%. At the cooling peak day and time, the BIPV window significantly reduced the cooling energy use, and a daylight-dimming system resulted in additional savings in electrical lighting energy use. Therefore, the BIPV window has a potential to downsize the system due to the reduced peak demands; and it may result in additional energy savings due to lower compressor's power consumption.
- The BIPV windows provided electricity power generation, decreased electric lighting energy use, decreased annual building loads, and reduced he system's cooling peak demand. As a consequence, the percent savings in comparison with the base-case window were about 12 to 21%. This indicates that the BIPV window with the daylight-dimming system provide great energy benefits for a code-compliant residential building. However, a cost analysis to evaluate economic benefits may be required to determine the optimal energy savings goals when using a daylight-dimming system for a BIPV window.

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