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Conceptualization of a Photovoltaic Powered Electrochromic Switching of a Multifunctional Glazing

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Abstract

A multifunctional glazing system has the potential to reduce the heat loss through a window with control of solar heat gain and daylight. Thus it can reduce both the cooling load and heating load depending on weather, occupancy and building construction. A photovoltaic (PV) panel can be used to generate energy to change the colour of the electrochromic (EC) material. Battery storage system has been included to activate the EC behaviour using stored solar electricity. PV area and cost can thus be smaller. As a window can be placed in different sides of a building, incident solar irradiation on a PV for a particular day and time and position was calculated. Modelling of battery and PV power output was done to determine the area of PV and number of battery system for different load conditions.

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Keywords: Vacuum glazing; Electrochromic glazing; Vacuum electrochromic glazing; Aerogel glazing; Photovoltaic electrochromic glazing; SHGC; *U* value; Windows; Battery, Photovoltaic; LPSP

1. Introduction

Fenestration has a significant role in achieving a required quality of life and comfort for building occupants. Windows offer visual amenity, comfort, privacy and control of light and air. Heat loss and heat gain both ensue through windows. Windows have a dynamic relation with external environment [1-3]; in a hot climate solar radiation entering through the window increases room temperature introducing a requirement for cooling. In a cold climate a window can give an overall heat loss increasing the heating demand. Windows also provide daylighting, solar heat gain coefficient (SHGC) can be controlled using shading devices, often of limited durability. A multifunctional glazing can have

- Electrochromic modulation of window transmittance

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- High insulation (i.e. low U value) using vacuum glazing, aerogel , multiple pane
- Daylight control
- Power generation from a photovoltaic panel

Figure1 shows two condition of multifunctional glazing. On the Left hand side a window is in a clear condition when it allows the entering solar radiation and on the right hand side is shown an opaque state limiting the entering solar radiation. Figure 2 depicts the possible different component parts of a Multifunctional glazing

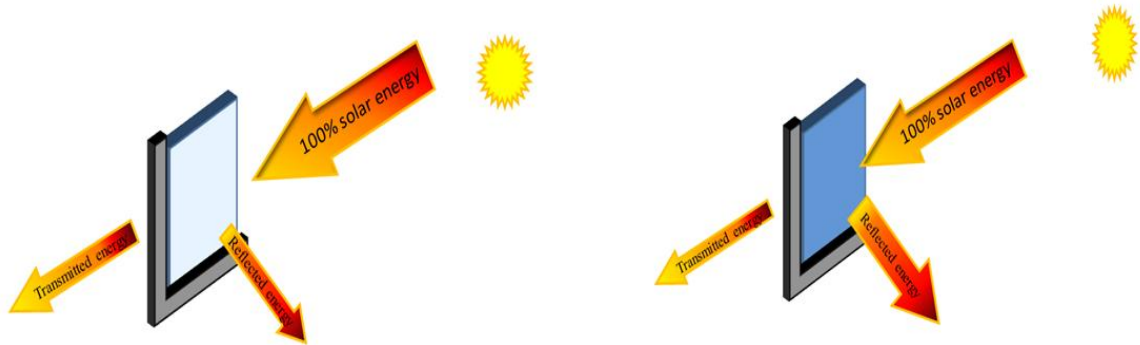


Figure. 1. Multifunctional evacuated glazing in clear and opaque state

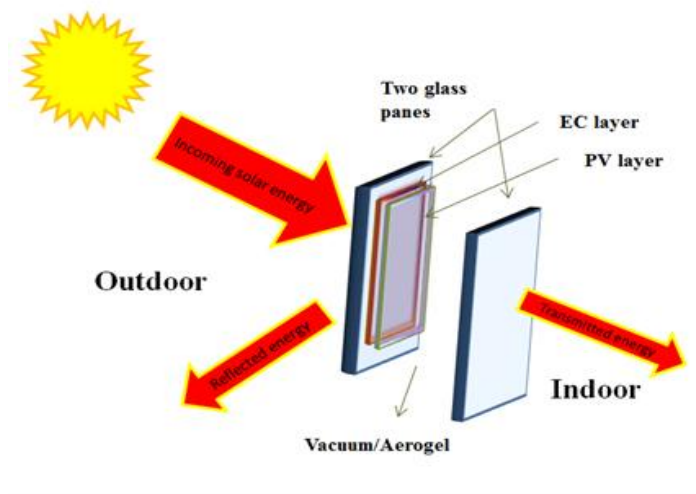


Figure. 2. Different layer of multifunctional evacuated glazing

Nomenclature

ϕ	Latitude (deg)	V	Voltage (V)
δ	Declination (deg)	I_{pv}	photo generated current (A)
γ	Azimuth angle of inclined plane (deg)	I_{sc}	Short circuit current (A)
β	Tilt angle of plane to ground (deg)	I_0	diode saturation current (A)
Ω	Angular displacement of sun (deg)	V_m	maximum voltage (V)
R_b	ratio between the flux of beam radiation incident on an inclined surface and on the horizontal surface	I_m	maximum current (A)
R_d	ratio of the flux of diffuse radiation falling on the tilted surface to that on the horizontal surface	V_{oc}	open circuit voltage (V)
q	Electron charge (1.6×10^{-19} C)	a	diode ideality factor
k	Stefan-Boltzmann constant ($1.38 \times 10^{-23} \text{m}^2 \text{kgs}^{-2} \text{k}^{-1}$)	R_s	series resistance (Ω)
T	Temperature ($^{\circ}\text{C}$)	R_{sh}	Shunt resistance (Ω)

1.1. Vacuum glazing

In 1989 at the University of Sydney [4] a vacuum glazing system was manufactured and tested [5-8]. Vacuum glazing consists of a vacuum between two glass panes separated by small pillars to withstand atmospheric pressure. Heat flows through the pillars are independent and parallel to the radiative heat flow between the glasses. Highly insulating vacuum glazing has a hermetic (leak free) edge sealing around the periphery of two glass sheets and a stable pressure (<0.1 Pa) between two glass sheets. Vacuum glazing up to 1m×1m in size had been produced having 0.90W/m²/K mid device thermal conductance compared to 1.3W/m²/K for double glazing [9]. Addition of transparent low emittance coatings reduce radiative heat transfer between the sheets [10] thus thermal resistance increased while the solar heat gain decreased [11]. Use of two low- e coatings does not reduce the overall heat transfer rate over a single low e coating layer. One layer of low e coating also reduces the overall system cost as low e coatings are costly [12]. Triple vacuum glazing systems have been theoretically studied [13, 14]. Such systems are not viable if cost of low-e and glass are considered. Moreover it will increase the overall weight of the system and can't control the daylighting and solar heat gain coefficient (SHGC).

1.2. Electrochromic Glazing

Electrochromic (EC) material includes an electrochromic cell which changes from being transparent to opaque state by redox reaction in the presence of applied voltage. Main purpose of electrochromic is to control the daylight and solar heat gain. In hot climatic conditions an EC window in coloured state

reduces the solar heat gain and enabling a building to consume less cooling energy. In cold climatic conditions an EC window should operate in a bleached state during a heating season and provides control over glare and overheating due to solar gain [15, 16].

1.3. Vacuum –Electrochromic Glazing

Vacuum glazing and electrochromic glazing have been combined [17]. This prototype (40cm×40cm) was able to achieve transparency from 63 % (bleached state) to 2 % (coloured state) with a mid-pane U value of $0.86\text{W}/\text{m}^2\text{K}$. It was found that to avoid intolerable over heating an EC layer between vacuum glazing an third glass pane should always face the outside environment [18]. Vacuum electrochromic glazing manufactured with three glass panes obviously needs external power to change colour.

1.4. Photovoltaic –Electrochromic Glazing

Photovoltaic (PV) combined with electrochromic glazing will eliminate the need for an external power supply to change the colour from a bleached state to coloured state. A 16cm^2 monolithic amorphous silicon based photovoltaic powered electrochromic window was able to modulate the transmittance more than 60% in visible range [19]. The necessary coloration and bleaching voltage was varied between 0.1V-1.3V. A semitransparent tandem photovoltaic –electrochromic device achieved colouring in less than one minute [20]. Three different approaches; stand-alone side– by-.side, monolithically integrated were combined with a dye sensitized TiO_2 solar cell and an electrochromic device by Deb et.al.2001. They found that the tandem structure encountered a short circuit current between deposited layer that made it difficult to produce large area devices [21, 22].

1.5. Aerogel Glazing

An aerogel is a translucent solid gel that exhibits high thermal insulation suitable candidate for low heat loss windows. In addition it has also low refractive index, and very low density. A glazing with monolithic aerogel achieved a heat loss coefficient less than $0.7\text{W}/\text{m}^2\text{K}$ for 15mm thick aerogel between two glass panes [23]. A new evacuated monolithic silica aerogel glazing was developed where silica aerogel evacuated to a rough vacuum of -10hPa. This glazing system achieved U - value below $0.5\text{W}/\text{m}^2\text{K}$, while solar energy transmittance was above 0.75 [24]. Schultz et. al. (2005) reported an aerogel glazing system which also achieved and overall heat loss coefficient below $0.7\text{W}/\text{m}^2\text{K}$ [25].

1.6. Component Synergy

A multifunctional low heat loss glazing will be combinations of some or all of these systems. Vacuum glazing is mainly used in cold climates, but can be used in hot climates if solar heat gain can be reduced by use of an electrochromic material. Thus the heat from room temperature is not transmitted due to the presences of vacuum insulation or aerogel insulation. Previous work has used three glass panes and three layers of low -e coating increasing the weight and cost of the system. Here it is proposed to use only two glass panes. Integrated photovoltaic will provide the necessary energy to change the colour of

electrochromic material. The use of low cost luminescent concentrating material (LSC) could further reduce the cost of the system.

2. Model description

2.1. Solar radiation model

Output of a PV array depends on the solar radiation incident on it and environment temperature and characteristics of PV module. The equation 1[26] is used to calculate total solar radiation on a surface of arbitrary orientation

$$I_T = I_b R_b + I_d R_d + \rho R_r (I_b + I_d) \tag{1}$$

$$R_b = \frac{\cos \theta_i}{\cos \theta_z} \tag{2}$$

$$R_d = \frac{1 + \cos \beta}{2} \tag{3}$$

$$R_r = \frac{1 - \cos \beta}{2} \tag{4}$$

Angle of incidence can be expressed by equation 5

$$\begin{aligned} \cos \theta_i = & \sin \delta \sin \phi \cos \beta - \sin \delta \cos \phi \sin \beta \cos \gamma + \cos \delta \cos \phi \cos \beta \cos \omega \\ & + \cos \delta \sin \phi \sin \beta \cos \gamma \cos \omega + \cos \delta \sin \beta \sin \gamma \sin \omega \end{aligned} \tag{5}$$

2.2. PV model

Equation 6 represents the ideal or Shockley equation [27]. Equivalent circuit diagram is shown in figure 3 (a).

$$I = I_{pv} - I_0 \left[\exp\left(\frac{qV}{akT}\right) - 1 \right] \tag{6}$$

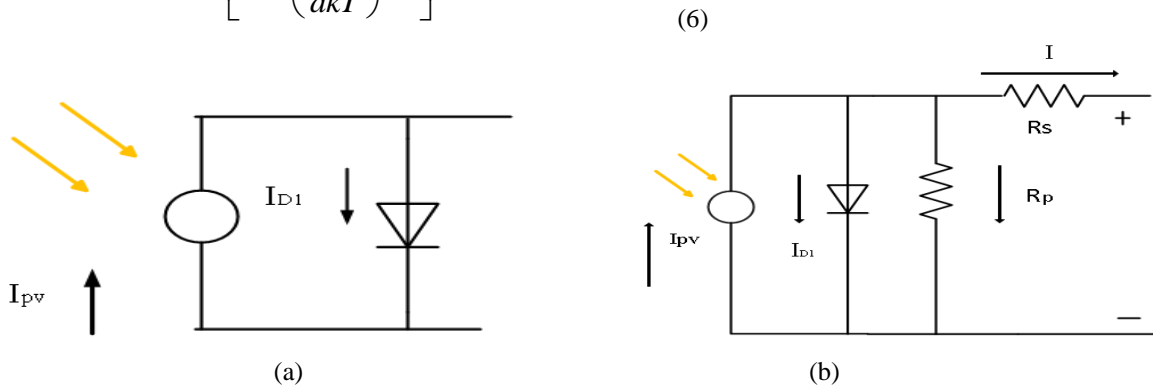


Figure. 3.(a) Equivalent circuit diagram of ideal diode; (b) equivalent circuit of a practical PV device

There are one-diode [28, 29] and two-diode models [30, 31] to evaluate the maximum power output from a PV cell. In case of two-diode model the extra diode represents recombination carriers. A three diode model also used to add more information not present in two diode model. Here a simplified one diode model [32] is used to reduce the need for unknown parameters and number of iterations.

An equivalent circuit of a practical PV device is shown in figure 3(b). Here I_{pv} and I_0 are the photovoltaic and saturation current while equation 7 represents the thermal voltage.

$$V_T = N_s k T / q \tag{7}$$

If cells are connected in parallel then total output current will increase and if cells are connected in series provide greater output voltage. Equation 8 represents the current output from a solar cell

$$I = I_{pv} - I_0 \left[\exp\left(\frac{qV}{akT}\right) - 1 \right] - \left(\frac{V + IR_s}{R_p} \right) \tag{8}$$

Where $I_{PV} = (I_{SCn} + K_i) \frac{G}{G_n}$ (9)

and $I_0 = \frac{(I_{SCn} + K_i) \Delta T}{\exp\left[\frac{V_{ocn} + K_v \Delta T}{aV_T}\right] - 1}$ (10)

2.3. Battery storage and PV material optimization

As the multifunctional window will be powered from just the PV source, a storage device is essential to activate the electrochromic behaviour using stored solar electricity. The PV area can then be smaller as it does not need to instantaneously satisfy the switching load. This PV source is fully dependent on the solar radiation, and temperature. In this scenario the battery charge estimation is complicated. Calculation of optimum of PV and capacity batteries are calculated here by loss of power probability concept (LPSP). If LPSP 0 the load will always be satisfied and when LPSP 1 load will never be satisfied [33,34]. State of charge was used here to control the overcharge and discharge case. We considered the battery charge efficiency is equal to round trip efficiency and discharge efficiency was set to equal to 1.

Energy generated by PV can be expressed as follows

$$E_{g(t)} = N_{PV} \cdot E_{PV(t)} \tag{11}$$

When PV generated energy is greater than load demand i.e. battery charging $E_{b(t)}$ is energy store in batteries in t hour time, $E_{b(t-1)}$ is energy store in battery in previous hour, $E_{L(t)}$ = load demand in hour t

$$E_{b(t)} = E_{b(t-1)} + (E_{g(t)} - E_{L(t)}) \cdot \eta_{batt} \tag{12}$$

When load demand is greater than PV generated energy i.e. battery discharging

$$E_{b(t)} = E_{b(t-1)} - (E_{L(t)} - E_{g(t)}) \tag{13}$$

Energy stored in batteries at any time t can be $E_{b\min} \leq E_{b(t)} \leq E_{b\max}$

When generation and available energy from battery both will insufficient to satisfy the load that deficit can be called loss of power supply [35].

$$LPS_{(t)} = E_{L(t)} - (E_{g(t)} + E_{b(t-1)} - E_{b\min}) \tag{14}$$

$$LPSP = \frac{\sum_{t=1}^T LPS_t}{\sum_{t=1}^T E_{L(t)}} \tag{15}$$

3. Result and Discussion

The solar irradiation, PV and battery model were validated with result of Ishaque et.al 2011 [36].and Shen 2009 [37]. Direct and diffuse solar irradiation data on horizontal plane for Dublin was used for a particular day (15th January 2011) with cloudy conditions. As the northern latitude (53.3428°N) global radiation has a large contribution from the diffuse component. Figure 4 shows the solar radiation from 9am to 4pm. A module kept in latitude angle and south facing to receive maximum incident solar irradiation. Calculation of different angle and orientation was possible for building façade and window application. Our PV model Figures 5 (a) represents the power-voltage and figure 5 (b) represents current-voltage curve for a north facing PV module. The data output from the solar irradiation model was used as input in PV model. The output from PV model was used for battery LPSP model and shown in figure 6.

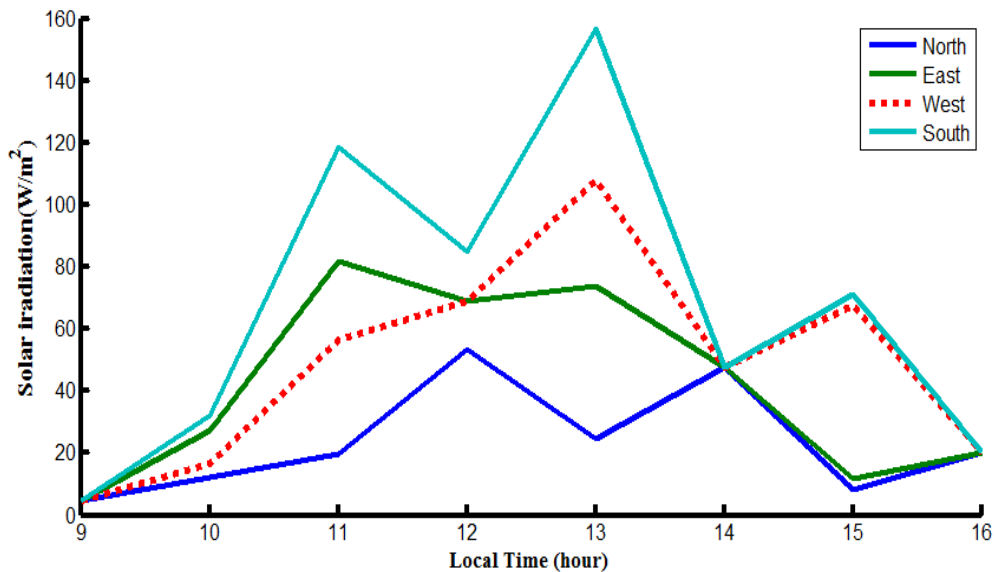


Fig. 4. Incident solar irradiation for Dublin on 15th January 2011 for different orientations

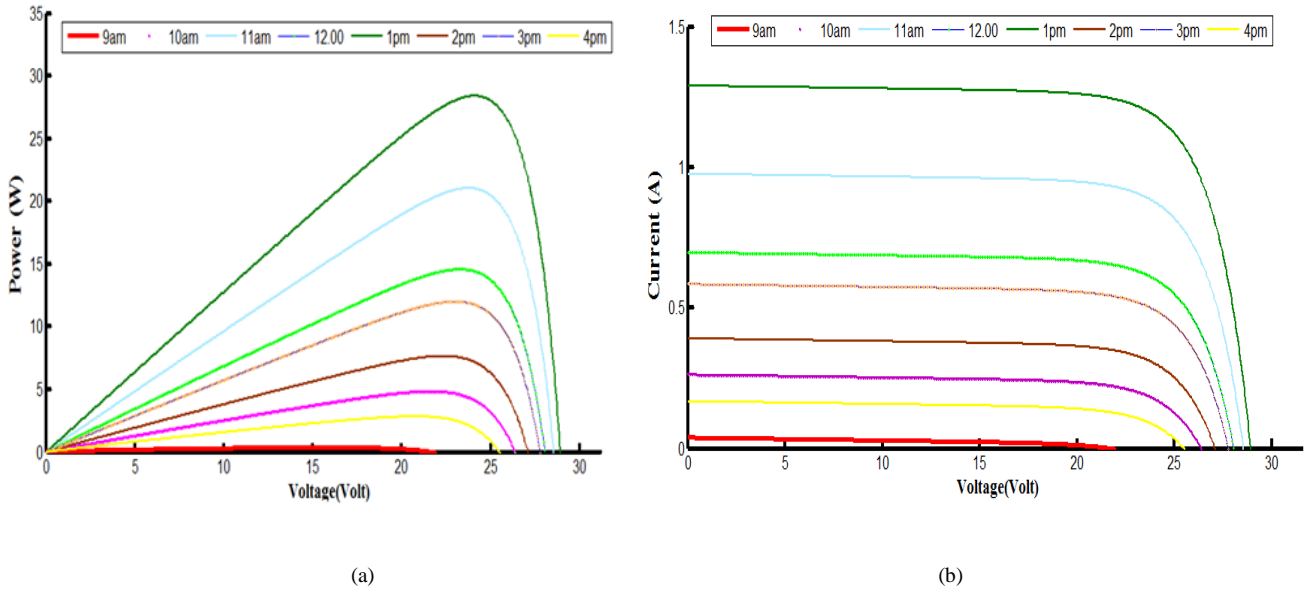


Fig. 5. North facing PV module (a) power voltage curve; (b) and I-V curve

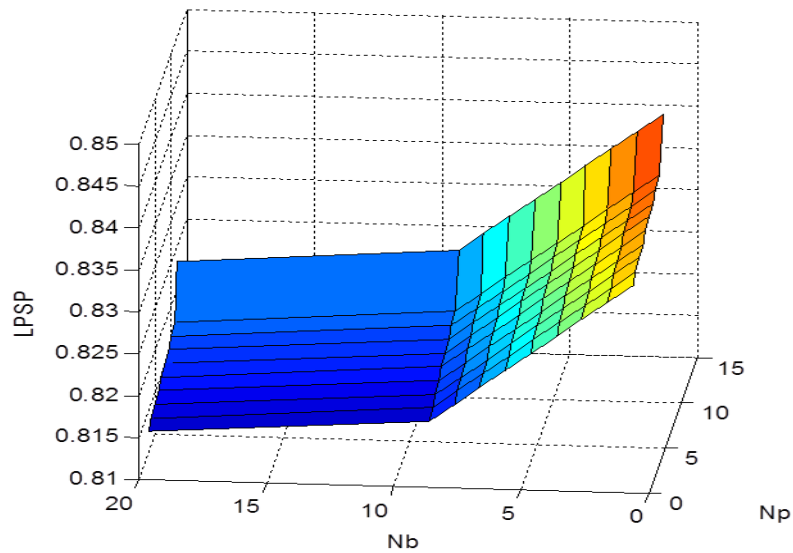


Fig. 6. Plot of different size combination of number of PV (N_p) panel and number of battery (N_b) at different LPSP values

4. Conclusion

This work presents a review on the concept of Multifunctional glazing device that can be applied under any climatic condition. Solar radiation on a tilted PV of a multifunctional glazing device was evaluated from Liu Jordan equation. For PV, one diode model was presented here which will be used to switch the EC material for a multifunctional glazing. Battery storage device was considered for the device to satisfy the instantaneous switching load. Loss of power supply probability method was adopted to optimize number of PV and number of battery requirement.

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