Total equivalent energy efficiency metric for building integrated photovoltaic and spectrum shifting windows

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Introduction

Solar windows with semitransparent photovoltaics provide light, sound and thermal controls, as well as electricity production. For evaluating the total efficiency of incident sunlight conversion into useful energy in the form of electric power and luminous flux, an agreed criterion is required. An efficiency metric is needed to encourage progress in solar windows for building integrated photovoltaics (BIPVs) and to enable energy efficiency comparisons of each technology. In this work, we present an efficiency metric that converts the luminous flux into energy at a rate that depends on whether the transmitted light meets a white light criterion. This total equivalent energy efficiency metric is formed by adding the equivalent luminous power to the electrical power and dividing the sum by the input power.

Developing Efficiency Metrics for Solar Windows

Figure 1 illustrates the logic steps in the development of the total equivalent energy efficiency metric with two types of light input (global (yellow arrow) and diffuse(grey) sunlight) on the left and two types ("Non-white" and "White") of comparison light as output on the right. The first comparison light choice is monochromatic green light with a wavelength of 555nm, which presents the maximum of the photopic response (luminous efficacy of 683 lm/W) [1]. This choice values the light only for its illumination value, excluding colour characteristics such as "whiteness" quality. The second choice is ideal white light, which is the truncated solar spectrum with luminous efficacy of 251 lm/W [1]. It meets the most stringent colour matching criteria and is the "gold standard" white light source. Equivalent luminous power is then converted from measured luminous flux and comparison light luminous efficacy.

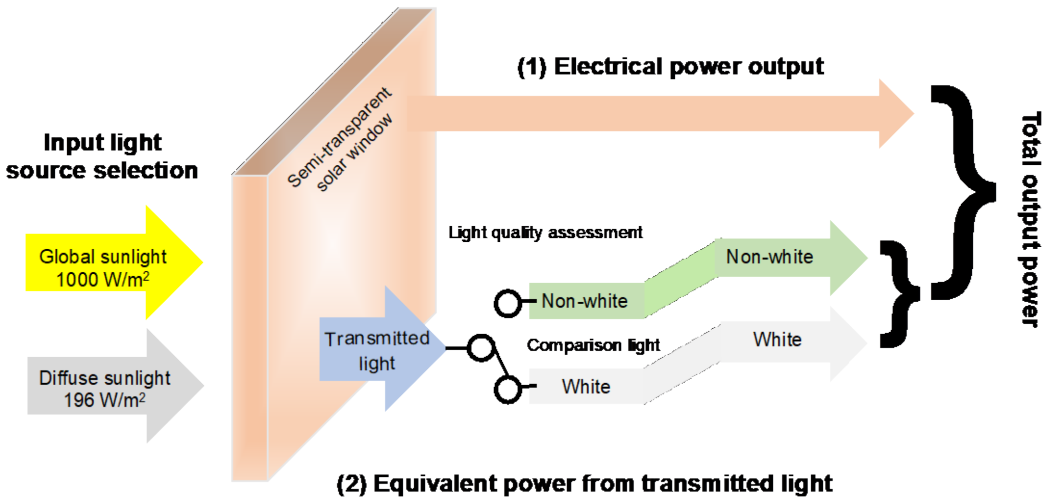

Figure 1: Illustrating the design of the total energy efficiency metric for combining electrical and light outputs through a semitransparent solar window. The total equivalent energy efficiency metric is the ratio of total equivalent power output divided by the input power.

To develop an equivalent energy efficiency metric for a BIPV solar window, the device must be assessed in terms of the harvested electrical power as well as the equivalent energy in the transmitted luminous flux. The electrical power output of the photovoltaic component is readily measured using methods developed for conventional photovoltaic technology, while the luminous flux is assessed in terms of the equivalent electric power that would be needed to achieve the same illumination of the room as assessed by the light adapted human eye. Since the eye is not equally sensitive to all wavelengths, it is useful to define a luminous efficacy V_e of a light beam as the ratio of the luminous flux in the beam to the total radiant power in the beam, measured in units of lumen per watt:

$$V_e = \frac{\int I_\lambda V_\lambda \, d\lambda}{\int I_\lambda \, d\lambda}$$

The total power output per unit area from a solar window P_{Total} is represented by the sum of the electrical power output $P_E$and the equivalent power of the transmitted illumination, the illumination power P_I . P_I is obtained from the luminous flux transmitted into the interior, F_{It}in lumen, then dividing it by the luminous efficacy V_{ec} of the chosen comparison light, in lumen per watt (Eq.4):

$$P_{Total} = P_E + P_I = P_E + \frac{F_{It}}{V_{ec}}$$

The *total equivalent energy efficiency metric* η_{BIPVE} of a BIPV window is obtained from the total equivalent power output per unit area of window (Eq. 4), divided by the incident power per unit area, the irradiance I_s:

$$\eta_{BIPVE} = \frac{P_E + P_I}{I_s} = \frac{P_E}{I_s} + \frac{F_{It}}{I_s V_{ec}} = \eta_{PCE} + \eta_{TE} = \eta_{PCE} + \frac{F_{It}}{I_s V_{ec}} = \eta_{PCE} + \frac{F_{It}}{\frac{F_{Ii}}{V_{ei}} V_{ec}} = \eta_{PCE} + \frac{F_{It}}{F_{Ii}} \frac{V_{ei}}{V_{ec}} = \eta_{PCE} + \eta_{luminous} \frac{V_{ei}}{V_{ec}}$$

η_{PCE} is the power conversion efficiency of the solar cell, and η_{TE} is the transmitted light equivalent energy efficiency. The incident radiation is either one sun global irradiation (AM1.5G) where I_s has the value 1000W/m^2 or indirect sunlight obtained from the difference between AM1.5G and AM1.5D where I_s has the value 196 W/m^2. V_{ei} is the luminous efficacy of the incident light and will be 105 lm/W for AM1.5G irradiation or 130 lm/W for indirect sunlight (AM1.5G-AM1.5D).

Our metric has advantages over previous metrics used to evaluate semitransparent BIPV devices such as the average visible transmittance (AVT). The AVT is the arithmetic mean of the transmission spectrum within an arbitrary wavelength range [2]. While AVT has subsequently evolved to take into account the response of the human eye to calculate a weighted average visible transmission [2] [3] [4], it is not an equivalent energy efficiency metric like our metric η_{BIPV} . Another metric that has been proposed for semitransparent solar cells is the simple product of AVT and power conversion efficiency (PCE), that has been termed the light utilization efficiency (LUE) [5]. Although the LUE takes into account both electrical and optical performance, it does not address the trade-off between them in a rigorous manner as our metric does.

We derived the upper limits of the metric with both global and diffuse sunlight inputs, finding there are two “sweet spots” when plotted as a function of bandgap. The first maximum occurs near a bandgap of 1.4-1.5eV where electrical power production is dominant. The second maximum occurs near 2.5eV where luminous power production is dominant. Efficiency limits of devices with thinned absorber are also presented in this work.

Evaluating Downshifting Windows Using the Total Equivalent Energy Efficiency Metric

Incorporating a spectrum shifter in solar windows is an attractive opportunity to improve the light power. A downshifting $(Ba,Sr)_2SiO_4:Eu^{2+}$ layer was added on a 2.3eV bandgap perovskite device at the sun facing side. Under diffuse sunlight, this device showed a total equivalent energy efficiency improvement of 0.7%. As a supplementary investigation, we measured the performance of a downshifting window without a photovoltaic component. When the window was facing away from the sun, we observed a greater luminous flux density than the incident light. This downshifting window can be regarded as a “super-window”. With respect to the total equivalent energy efficiency, the downshifting window is more energy efficient compared to a normal glass window under diffuse sunlight, no matter the transmitted light is white (55% as to 39%) or non-white (20% as to 14%).

Conclusion

The significance of this work is that the new metric provides useful and comprehensive guidelines for the glazing industry to select the most appropriate solar cell for partially transparent solar windows. The knowledge gained in this work creates opportunities for product design that strikes a balance between electrical and lighting requirements. The findings are translatable to other integrated photovoltaics. Successful applications of highly efficient solar windows could not only improve aesthetic values but also introduce energy cost reduction to enter a green and sustainable era.

Reference

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