The solar energy potential of window-mounted semi-transparent PV in the urban environment

Maria Panagiotidou[1,2], Jin Zhou[3] and Jacek Jasieniak[1,2]
[1]ARC Centre of Excellence in Exciton Science, Monash University, Clayton, Victoria, 3800, Australia
Department of Materials Science and Engineering, Monash University, Clayton, Victoria, 3800, Australia
[3]Department of Civil Engineering, Monash University, Clayton, Victoria, 3800, Australia

Abstract

The building sector is accountable for more than 35% of the global energy demand and almost 40% of the GHG emissions (UN Environment and IEA, 2017). While urban areas accommodate more than half of the building stock, they offer great opportunities for on-site energy production and use while minimising transmission losses. Thus, a widely recognized opportunity to reduce carbon emissions globally is to increase the resource efficiency of urban neighbourhoods.

In urban areas, building envelopes are used to capture and transform the solar irradiation into electricity and heat. Quantifying the solar irradiation that reaches the building envelopes and assessing building surfaces' potential for photovoltaic electricity production has received much attention in the past decades. A large number of studies focus on the calculation of the solar potential of building roofs (Compagnon 2004; Jakubiec and Reinhart, 2013; Redweik et al., 2013; Singh and Banerjee, 2015; Rodríguez et al., 2017), others estimate the potential of building integrated photovoltaics (BIPV) (Fath et al., 2015; Saretta et al., 2020), while few of them look at the combined potential of roofs and facades (Catita et. al, 2014; Mohajeri et al., 2016; Brito et al., 2017, Freitas et al., 2020). In a building scale, the performance of window-mounted semi-transparent photovoltaics (ST-PV) was studied by Didone et al. (2013) and Mesloub et al. (2020), however, to the best of the authors' knowledge, the potential of ST-PV in the urban environment has not been investigated. Addressing that knowledge gap, the present study explores the energy potential of high efficiency ST-PV in the urban context.

A computer simulation approach was employed to quantify and compare the annual electricity yield of the building envelope areas (roofs, walls and windows) between three PV technologies — roof-mounted PV, facade BIPV, and window-mounted ST-PV. The 3D model of representative blocks of four inner Melbourne neighbourhoods (Melbourne CBD, East Melbourne, Carlton and Port Melbourne) was built in Rhino/Grasshopper environment, based on the Census of Land Use and Employment (CLUE) database (City of Melbourne, 2018). Each property was categorised under one of the 48 different building archetypes, according to the predominant land use, the building age and height of CLUE database, inside the ArcGIS environment. The archetypes were developed by Seo et al. (2014) and enriched with construction characteristics, including the window-to-wall ratio (WWR), based on expert knowledge, by Stephan and Athanasiadis (2017). At the first step, the annual cumulative solar irradiation (kWh m^{-2}) for the facade and roof surfaces (spatial resolution of 1 m^2) of each block structure was calculated, using the EnergyPlus (2020) weather data file for Melbourne. For that purpose, the Ladybug component 'Radiation Analysis' that interfaces Daysim/Radiance software, was employed, considering the shading effect of the surrounding buildings. Three minimum irradiation threshold values were applied to the three PV technologies (see Table 1 and Figure 1), in order to respond to the present technical limitations and economic factors, as well as the future technical innovation and economic progress of solar technologies. Finally, the annual electricity yield was calculated, for the surfaces that meet the threshold requirement, for the three PV technologies, using the Ladybug components 'Photovoltaic Surface' and 'DC-to-AC Derate Factor', that interface PVWatts software, as well as 'Sunpath Shading'. For the calculations, typical values of roof-mounted PV and BIPV were assumed and are presented in Table 1. For the window-mounted ST-PV, the performance properties of perovskite solar modules were considered. Compared to other ST-PV technologies under development, perovskite solar cells demonstrate high power efficiency of over 12%, while achieving peak transmission of over 75% (Bailie et al., 2015).

The main results regarding the annual electricity yield per surface category (roof, wall and window) of the representative blocks, normalised by the total footprint area of buildings, are presented for the selected range of irradiation threshold (Figure 1). It is noticed that urban blocks located in low-rise neighbourhoods of Melbourne, such as East Melbourne and Port Melbourne indicate a low potential for ST-PV, compared to BIPV and roof-mounted PV. This can also be attributed to their low WWR related to their predominant land use, which is residential and warehouse respectively. On the other hand, urbans blocks located in middle and high-rise neighbourhoods, such as Carlton and Melbourne CBD, indicate greater potential for ST-PV. Apart from the obvious reason of their larger facade areas, due to the greater building height, an additional reason is the higher WWR of the predominant land use, which is mainly office and retail. It can also be noticed that there is a positive linear correlation between the annual electricity yield of ST-PV and the urban compactness indicator 'volume-area ratio' (volume: the total building volume, area: the block area) and a strong negative correlation between the roof-PV and the 'volume-area ratio'.

Future research could address the limitations of the present study, which is mainly the low level of detail of the 3D models. With the development of LiDAR technology and enhanced computing power, more detailed models can be produced for large urban areas, also with improved simulation accuracy.

Table 1. Properties of the simulated photovoltaic technologies.

Parameter	Roof-PV	BIPV	ST-PV
Technology	Monocrystalline silicon	Monocrystalline silicon	Perovskite
Efficiency (%)	19	19	10
Temperature coefficient (P_{max}) (%/°C)	-0.45	-0.45	-0.20

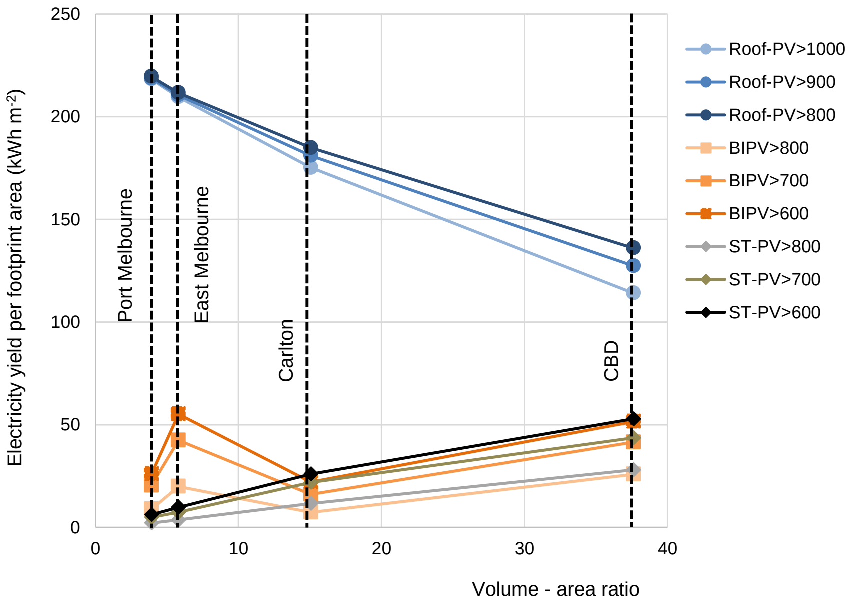

Figure 1. Comparison of annual electricity yield produced by roof, facade wall and window areas for a given technology (roof-PV, BIPV, ST-PV) associated with the compactness indicator (volume-area ratio) of the representative blocks of four inner Melbourne neighbourhoods at various annual irradiation thresholds in units of kWh m^{-2}.

References

Bailie, C., Christoforo, G., Mailoa, J., Bowring, A., Unger, E., Nguyen, W. et al., 2015, 'Semi-transparent perovskite solar cells for tandems with silicon and CIGS', *Energy and Environmental Science*, 8, pp. 956-963.

Brito, M.C., Freitas, S., Guimarães, S., Catita, C. and Redweik, P., 2017, 'The importance of facades for the solar PV potential of a Mediterranean city using LiDAR data', *Renewable Energy*, 111, p85-94.

Catita, C., Redweik, P., Pereira, J. and Brito, M.C., 2014, 'Extending solar potential analysis in buildings to vertical facades', *Computers and Geosciences*, 66, p1-12.

City of Melbourne, 2018, 'Census of Land Use and employment'.

Compagnon, R., 2004, 'Solar and daylight availability in the urban fabric', *Energy and Building*s, 36, p321-328.

Didoné, E.L. and Wagner, A., 2013, 'Semi-transparent PV windows: A study for office buildings in Brazil', *Energy and Buildings*, 67, pp. 136–142.

EnergyPlus, 2020, Weather Data by Location | *EnergyPlus*. Available at: https://energyplus.net/weather-location/southwest_pacific_wmo_region_5/AUS//AUS_VIC.Melbourne.948680_RMY (Accessed: 22 September 2020).

Freitas, S., Cronemberger, J. and Soares, R.M, (2020), 'Modeling and assessing BIPV envelopes using parametric Rhinoceros plugins Grasshopper and Ladybug', *Renewable Energy*, 160, pp. 1468–1479.

Jakubiec, A. and Reinhart, C., 2013, 'A method for predicting city-wide electricity gains from photovoltaic panels based on LiDAR and GIS data combined with hourly Daysim simulations', *Solar Energy*, 93, pp. 127-143.

Mesloub, A., Albaqawy, G. A. and Kandar, M. Z., 2020, 'The optimum performance of Building Integrated Photovoltaic (BIPV) Windows under a semi-arid climate in Algerian Office Buildings', *Sustainability*, 12(4) 1654.

Mohajeri, N., Upadhyay, G., Gudmundsson, A., Assouline, D., Kämpf, J. and Scartezzini, JL., 2016, 'Effects of urban compactness on solar energy potential', *Renewable Energy*, 93, pp. 469-482.

Redweik, P., Catita, C. and Brito, M., 2014, 'Solar energy potential on roofs and facades in an urban landscape', *Solar Energy*, 97, p332-341.

Rodríguez, R., Duminil, E., Ramos, J. and Eicker, U., 2017, 'Assessment of the photovoltaic potential at urban level based on 3D city models: A case study and new methodological approach', *Solar Energy*, 146, p264-274.

Saretta, E., Bonomo, P. and Frontini, F., 2020, 'A calculation method for the BIPV potential of Swiss façades at LOD2.5 in urban areas: A case from Ticino region', *Solar Energy*, 195, pp. 150–165.

Seo, S., Foliente, G., Lipkin, F., Yum, K., Anticev, J., Egan, S. and Reedman L., 2014, 'Inner Melbourne Energy Consumption 2011-2026: Baseline and Future Scenarios Forecasts for the Residential and Commercial Sectors', CSIRO, Melbourne.

Singh, R. and Banerjee, R., 2015, 'Estimation of rooftop solar photovoltaic potential of a city', Solar Energy, 115, pp. 589-602.

Stephan, A. and Athanassiadis, A., 2017, 'Quantifying and mapping embodied environmental requirements of urban building stocks', *Building and Environment*, 114, p187-202.

UN Environment and IEA, 2017, 'Towards a zero-emission, efficient, and resilient buildings and construction sector. Global status report 2017'.