The design orientation and shading impacts on rooftop PV economics in the urban environment: a case study in Melbourne, Australia

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Abstract: To deal with the environmental and energy issues, many researchers found high potential of adopting building photovoltaic (PV) systems in urban areas, especially on building rooftop. However, the optimal energy output performance is impacted by the usable roof area, layout of PV arrays, and shading ratio considering high city density. This study aims to understand the impacts of design orientation and shading in the urban environment on rooftop PV's economic performance. This study carries out a case study in Melbourne with 15 PV designs under three shading conditions to generate a total of 45 scenarios. Through lifecycle cost analysis including net present value (NPV), NPV per kW and payback year (PB) the results show the best and worst design scenarios under different shading conditions and the maximum shading loss that makes NPV become zero. This study reveals that in Melbourne: For buildings facing north, the rooftop PV system should also be oriented north to achieve the best economic performance. If the building orientation is 20 degrees counter-clockwise from true north, the recommended azimuth angle of the PV system is 10 degrees towards east. In order to enhance the ability to sustain shading loss, the azimuth angle of PV system is also suggested to be 10 degrees towards east.

Keywords: Building Photovoltaics; orientation; shading analysis; economic analysis.

1. INTRODUCTION

It is widely accepted that increasing renewable energy sources (RESs) in the urban context is of great significance to improve the sustainability of a city. Among all the available RESs, solar photovoltaics (PV) energy is one of the most promising candidates thanks to the continuous cost reduction and technological improvement (Freitas et al., 2018). Rooftop PV systems are very common in urban areas due to the easy installation. A well-designed rooftop PV system cannot only bring great environmental benefit but also become an investment choice to adding value to building owners.

There are a number of factors that require to be considered to produce the most appropriate design to maximise PV system outputs. The tilt angle and azimuth angle of the PV arrays are considered as the most significant design parameters, which have the direct influence on obtaining the solar irradiation and energy outputs (Jantsch et al., 1991; Bhattacharya et al., 2014; Singh and Banerjee, 2016). A large amount of research has investigated the optimal tilt angle and azimuth angle for a certain location, such as Saudi Arabia (Kaddoura et al., 2016), Turkey (Bakirci, 2012), Canada (Rowlands et al., 2011) and Iran (Talezadeh et al., 2011). One common practice is that the tilt angle equals to the geographic latitude and the azimuth angle are the due south in the northern hemisphere for a fixed PV array (Rowlands et al., 2011). However, when it comes to the rooftop PV design in urban areas, it is ignored that the building orientation may affect the usable roof area for PV system. There could be conflict between the building orientation and the optimal layout of PV array. Many cities had their metropolitan planning scheme a long time ago, which pre-determined the general building orientations. Taking Melbourne as an example, the “Hoddle grid” is the layout of streets in its central business district (CBD), which was established in 1837 and became the first formal town plan of Melbourne (University of Melbourne, 2008; City of Melbourne, 2012). There are two main building orientations in Melbourne. In this densely-built district of Melbourne, majority of buildings are aligned with the layout of the streets which is 20 degrees counter-clockwise from true north. Outside of the CBD, the majority of buildings are oriented at approximately 10 degrees clockwise from true north (National Centers For Environmental Information, 2018).
The capacity of a PV system is highly impacted by the number of PV panels placed on the available roof area. To achieve the maximum number of PV panels, the orientation of the PV array, namely the azimuth angle, is supposed to equal to the building orientation. However, the amount of annual solar irradiation varies according to the azimuth angle. The rule of thumb is that the surface facing due-south achieves the most in the northern hemisphere, and vice versa in the southern hemisphere (Mondol et al., 2007). There is limited research conducting economic assessment on the optimal design for rooftop PV in urban areas, taking both main building orientations of the city and PV penal azimuth into consideration.

Meanwhile, shading in the urban environment can have a bigger influence on the PV system performance than any other design parameters (Horn, 2011). Shading is a major challenge imposed by surrounding obstruction like taller neighboring buildings or trees. Especially in the urban environment, shading is becoming a major risk. As cities grow bigger and buildings get taller, the likelihood of overshadowing buildings is higher which will result in great energy losses. Shading challenges could be the difference between a viable and nonviable PV project. To guide the deployment of PV systems, many studies investigated the solar potential of cities around the world (Compagnon, 2004; Redweik et al., 2013; Sarralde et al., 2015; Mohajeri et al., 2016; Wong et al., 2016). Most of them evaluated the availability of the solar irradiation under the impact of shading by surrounding buildings through geographic information system (GIS)-based methods (Melius et al., 2013). Some analysed the shading effects on the system yield and performance ratio reduction through experiment or software (Zomer et al., 2014; Frontini et al., 2016; Zomer et al., 2016; Bana and Saini, 2017). However, there is a lack of research associating the shading effect with the economic performance of rooftop PV systems especially in high density urban environment.

Hence, this study aims to investigate the impacts of design orientation and shading in the urban environment on rooftop PV's economic performance. A case study is conducted in the city of Melbourne, Australia. Fifteen PV design scenarios are developed by changing the combination of the building orientation and PV orientation. Three shading conditions are established to represent different shading probability in the urban areas. A life cycle cost-benefit analysis including net present value (NPV), NPV per kW and payback year (PB) is carried out to study the impacts of shading, building orientation and azimuth angle of PV system. The maximum shading loss that each PV system can withstand to maintain financially feasible is also analysed. The research process is explained in the next section, followed by the results and discussion. The conclusions of the study can benefit both the investors as well as the urban planners.

2. INVESTIGATION PROCESS

The case building of this investigation belongs to an educational institute in the urban area of Melbourne, Australia. The total built-up area of this building is approximately 1,131 m². Figure 1 illustrates the case building (in blue) in the selected urban block. As shown in Figure 1, the surrounding environment of the case building can be considered as a typical example of modern urban environment, with higher and lower buildings all around the case building. The height of the case building is approximately 6.9m, while the height of surrounding building varies from 3.1m to 29m. The case building is selected also because it has regular rectangle which aligns with the prevailing building designs. The shading condition of the selected areas is also analysed and discussed in Section 2.2. The proposed PV systems are located on the roof of the case building. The design scenarios are shown in Figure 2 and summarised in Table 1.

Multiple data sources and tools were utilised in the study to carry out the economic analysis: (1) Building drawings and information were collected from the educational institute in order to build up a SketchUp model of the case building and its surrounding environment. Google Earth was also used to assist the modelling process. (2) Detailed information of the selected PV module was obtained from a third-party PV design firm in Melbourne, who can provide the professional industry knowledge to the designs. (3) Fifteen design scenarios were specially developed for the urban environment in
Melbourne, which takes building orientation and PV panel orientation into consideration (see Section 2.1). Meanwhile, there are three different shading conditions developed for the study (see Section 2.2). (4) There are 15 scenarios of PV layouts proposed through the Skelion, which is a SketchUp plugin software with expertise in PV system design in 3D modelling. The explanation of the design process is provided in Section 2.1. (5) After the PV designs were developed, PV suppliers and installers were approached to obtain the capital cost information. A local utility provider advised the electricity price and Feed-in-tariff was obtained from the government website. (6) The hourly building consumption data are provided by the building owner. (7) Solar irradiation data were obtained from the NREL's PVWatts Calculator (NREL, 2018), which was used for energy output calculation. (8) Energy outputs were calculated based on the solar irradiation, system efficiency and loss. Energy consumption and output data were compared to identify the possible energy export to the public grid. (9) The Net Present Value (NPV), NPV per kW and Payback year (PB) were conducted to show the economic performance of all the designs. Design scenario that has the best or worst economic performance was identified. (10) The maximum shading loss was calculated for each design scenario when the NPV became negative.

2.1 Developing design scenarios

This study focuses on the impact of the building orientation and PV panel orientation (azimuth). Hence, the tilt angle of all the proposed PV design remains the same. Based on Rowlands et al. (2011), the tilt angle is set to be 38 degrees, which equals to the geographic latitude of Melbourne. As shown in the summary table (i.e. Table 1), the B represents the building orientation while the A stands for the PV azimuth angle. For example, the B0+A0 mean the combination of building facing the true north and the PV azimuth angle of zero. This setting remains the same across this paper. These 15 design scenarios can help to develop a relatively holistic understanding of rooftop PV design in the urban areas of Melbourne.

In terms of building orientation, there were three groups, namely true north, 10 degrees clockwise from true north and 20 degrees counter-clockwise from true north. The latter two were included to align with the typical building orientations in Melbourne. In the SketchUp model, the orientation of case building was changed while the surrounding environment remained the same. Regarding the azimuth angle of the PV design, we chose five sets of azimuth angle from 20 degrees counter-clockwise from true north (340) to 20 degrees clockwise from true north (20).

The PV system design of each scenario was made with the principle to install as more PV panels as possible. A popular Polycrystalline silicon PV product is selected for the application. The specification of the PV module used in the study is presented in Table 2. The distance for all the scenarios is set to guarantee all PV panels can achieve at least 6-hour sunlight at the winter solstice. Based on the PV selection and distance setting, the design results of all 15 scenarios are generated and summarised in Table 1. The results show that the number of PV panels in the scenarios of all three building orientations reaches the maximum when the azimuth angle of PV panel is zero. When the PV arrays parallel to the building orientation, scenario B10+A10 has the second most PV panels among all five B10 scenarios while scenario B340+A340 has the second least panels among all five B340 scenarios. Regardless of the building orientation, the number of PV panels reach the maximum when the PV azimuth angle is zero (i.e. facing north). The main reason lies in the distance between each PV

![Figure 2: The 3D models for all design scenarios.](image)
array. Suitable space should be provided between arrays to avoid shading effect caused by a front array on the back array. The design results show that the distance between two PV arrays is shortest when the PV arrays face the north, which maximizes the roof utilisation area.

<table>
<thead>
<tr>
<th>Name</th>
<th>Building orientation</th>
<th>PV azimuth angle</th>
<th>Number of PV panels</th>
<th>System capacity (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0+A0</td>
<td>0</td>
<td>0</td>
<td>220</td>
<td>55</td>
</tr>
<tr>
<td>B0+A10</td>
<td>0</td>
<td>10</td>
<td>197</td>
<td>49.25</td>
</tr>
<tr>
<td>B0+A20</td>
<td>0</td>
<td>20</td>
<td>177</td>
<td>44.25</td>
</tr>
<tr>
<td>B0+A340</td>
<td>0</td>
<td>340</td>
<td>177</td>
<td>44.25</td>
</tr>
<tr>
<td>B0+A350</td>
<td>0</td>
<td>350</td>
<td>199</td>
<td>49.75</td>
</tr>
<tr>
<td>B10+A0</td>
<td>10</td>
<td>0</td>
<td>216</td>
<td>54</td>
</tr>
<tr>
<td>B10+A10</td>
<td>10</td>
<td>10</td>
<td>203</td>
<td>50.75</td>
</tr>
<tr>
<td>B10+A20</td>
<td>10</td>
<td>20</td>
<td>186</td>
<td>46.5</td>
</tr>
<tr>
<td>B10+A340</td>
<td>10</td>
<td>340</td>
<td>178</td>
<td>44.5</td>
</tr>
<tr>
<td>B10+A350</td>
<td>10</td>
<td>350</td>
<td>190</td>
<td>47.5</td>
</tr>
<tr>
<td>B340+A0</td>
<td>340</td>
<td>0</td>
<td>209</td>
<td>52.25</td>
</tr>
<tr>
<td>B340+A10</td>
<td>340</td>
<td>10</td>
<td>192</td>
<td>48</td>
</tr>
<tr>
<td>B340+A20</td>
<td>340</td>
<td>20</td>
<td>175</td>
<td>43.75</td>
</tr>
<tr>
<td>B340+A340</td>
<td>340</td>
<td>340</td>
<td>186</td>
<td>46.5</td>
</tr>
<tr>
<td>B340+A350</td>
<td>340</td>
<td>350</td>
<td>201</td>
<td>50.25</td>
</tr>
</tbody>
</table>

Note: B means the building orientation; A means the azimuth angle of the PV arrays.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Cell</td>
<td>Polycrystalline silicon 156 × 156 mm (6 inches)</td>
</tr>
<tr>
<td>No. of Cells</td>
<td>60 (6 × 10)</td>
</tr>
<tr>
<td>Dimensions</td>
<td>1640 × 992 × 35mm (64.6 × 39.1 × 1.4 inches)</td>
</tr>
<tr>
<td>Front Glass</td>
<td>3.2 mm (0.13 inches) tempered glass</td>
</tr>
<tr>
<td>Module Efficiency</td>
<td>15.4%</td>
</tr>
<tr>
<td>Maximum Power at STC (Pmax)</td>
<td>250 W</td>
</tr>
</tbody>
</table>

2.2 Determining shading conditions and maximum shading loss

The shading effect on the PV system in many studies refers to the solar irradiance loss or the generation loss due to shading effect, usually in the form of percentage (Woyte et al., 2003; Loulas et al., 2012; Nguyen and Pearce, 2012). Nguyen and Pearce (2012) investigated the shading effect at municipal scale in downtown Kingston, Ontario, showing that shading leads to a 25% generation loss averaged over 12 months. Loulas et al. (2012) studied the shading loss of rooftop PV system on a building block in Greece. According to their study, the annual performance loss due to shading varied from approximately 8% to 23%. A similar investigation on the shading loss was carried out for the block where the case building is located (Yang and Carre, 2018). The result of the study showed that in this building block the average annual performance loss of rooftop PV system 16%. Deline et al. (2012) also indicated that in an typical urban environment, the annual shading loss is 7%, 19% and 25% respectively under the light shading, moderate shading and heavy shading scenarios. Therefore, this study adopts the three shading impact patterns to not only reflect on the current urban environment in Melbourne, but also provide indications to urban development changes and other cities in Australia. Furthermore, this study investigates a maximum shading loss that makes each design scenario financially unattractive (i.e. the NPV becomes negative) through the cost-benefit analysis. The results of maximum shading loss indicate the ability of each PV design scenario to sustain the shading loss in the urban environment.
2.3 Cost-benefit analysis

A 25-year cost-benefit analysis is carried out to study the actual value of all 15 PV designs. The cost consists of the initial investment cost of each system and the maintenance cost during the 25 years. The cost information regarding PV system was obtained from local PV suppliers and installers.

To calculate the benefit of the PV system, the first step is to calculate the energy output of the PV system using the Equation (1).

\[ E = A \times r \times H \times PR \] (1)

Where:

- \( E \) = the energy output in kWh;
- \( A \) = the total solar cell area in m\(^2\);
- \( r \) = the PV product efficiency in percentage;
- \( H \) = the hourly solar radiation in kWh/m\(^2\);
- \( PR \) = the system performance ratio.

The corresponding statistics of \( H \) used in each scenario were collected from a popular solar modelling tool – PVWatts (NREL, 2018). \( H \) represents the actual solar irradiation without any impact of building shading. The shading loss in the study is applied on the PR, which PR equals to 90%\(^*\)\((1\text{-shading loss})\). 90\% is the system performance ratio provided by the PV supplier. Three shading losses are examined, which are 7\% for light shading, 19\% for moderate shading and 25\% for heavy shading.

The second step is to compare the energy out with the building energy consumption. The building energy consumption of every 15-minute interval was measured for one year. The hourly energy consumption data were generated from the original data and were compared with the hourly energy output. If the energy output exceeds the building consumption, the surplus energy will be sold to the public grid at the price of Feed-in-Tariff set by the government.

The final equation of the benefit generated by the PV system is shown in Equation (2). Detailed information used in the study is shown in Table 3.

\[ B(n) = \sum_{25} ep_h \times (1 + \Delta ep)^n \times E_1(h) + FIT \times E_2(h) \] (2)

Where:

- \( n \) = the number of the year;
- \( ep \) = the electricity price of that hour;
- \( \Delta ep \) = the compounded growth rate of the electricity price of Melbourne calculated from the government report (Australian Energy Regulator, 2017);
- \( E_1(h) \) = the hourly energy generation using Equation (1) and is consumed by the building;
- \( FIT \) = the Feed-in-Tariff set by the government (State Government of Victoria, 2018);
- \( E_2(h) \) = the surplus energy sold to the public grid.

### Table 3: The benefits of applying PV designs.

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity rate</td>
<td>0.14AUD per kWh (0:00-7:00)</td>
</tr>
<tr>
<td></td>
<td>0.19AUD per kWh (7:00-24:00)</td>
</tr>
<tr>
<td>Electricity growth rate</td>
<td>5.42% per annum (Australian Energy Regulator, 2017)</td>
</tr>
<tr>
<td>Feed-in-Tariff</td>
<td>0.113AUD per kWh (State Government of Victoria, 2018)</td>
</tr>
</tbody>
</table>

The NPV, NPV per kW, PB and IRR are selected for the cost-benefit analysis in the study. Equation (3) is used to calculate the NPV in the study. To compare each scenario with different PV capacities, the NPV per kW is applied in the following sections to standardize the comparison instead of the NPV. The PB is the number of the year when the NPV become positive.

\[ NPV = -C_0 + \sum_{n=1}^{N} \frac{B_n}{(1+r)^n} - \sum_{n=1}^{N} \frac{M_n}{(1+r)^n} \] (3)

Where:

- \( C_0 \) = the initial investment cost;
- \( B(n) \) = the benefit generated by the PV system using Equation (2);
- \( M_n \) = the maintenance cost, which is assumed to be the cost of changing the invertors every 10 years;
- \( r \) = the discount rate, which is assumed to be 7\% in this study (Office of Best Practice Regulation, 2016).
3. RESULTS AND DISCUSSION

In this section, the results of the study are presented and discussed, which are conducted in two ways: (1) the economic performance of 15 different design scenarios under three shading conditions, and (2) the maximum shading loss that makes the system financially unviable.

3.1 Three shading conditions

The results of the NPV, NPV per kW and PB of all the scenarios under three shading conditions are illustrated in Figure 3. In general, the results show a consistent pattern under three shading conditions. When the building is facing north (i.e. B0), the NPV of north PV azimuth (i.e. A0) is the highest while that of A340 is the lowest under three shading conditions. Scenarios of B10 and B340 show the same outcomes. In terms of NPV per kW, among all B0 scenarios, the A20 has the best NPV per kW while A340 has the worst under each shading condition. However, B10+A10 and B340+A10 are the best NPV per kW among their groups.

Figure 3: The NPV, NPV per kW and Payback year of all the scenarios under three shading conditions.

In order to better comparing the performance of all 15 design scenarios, a summary table is generated as shown in Table 4. In the table, the best and the worst design scenarios of three shading conditions are listed. The percentage difference between the two scenarios is also provided. According to Table 4, scenario B0+A0 has the biggest system capacity, which also means that B0+A0 has the largest area of the solar cells and the highest initial investment cost. By contrast, scenario B340+A20 has the smallest system capacity. However, the economic performance of a system does not purely depend on the system capacity. In terms of NPV, scenario B0+A0 is the best while B0+A340 is the worst under all three shading conditions. The percentage difference between the best and worst NPV increases from 25.95% to 29.16% when the shading loss grows. Regarding payback year, there is no huge difference between each scenario under three shading conditions. All scenarios can be breakeven in the 11th year under light shading and 14th year under heavy shading. Since the 15 scenarios have a variety of system capacities based on the available roof areas, the NPV per kW can provide a better understanding of the system benefit per unit. From the perspective of performance per system capacity, the B340+A10 performs better than other scenarios while B340+A340 has the worst economic benefit per kW under all three conditions. The difference of the NPV per kW grows slightly as the shading loss becomes larger. One reason that the B0+A0 has the
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largest NPV while B340+A10 has the best unit benefit is the latter scenario has more energy consumed than sold. For buildings in Melbourne CBD area (i.e. B340), the result indicates that the recommended azimuth angle for rooftop PV system is 10 degrees towards east under the current shading condition (i.e. moderate shading) and heavy shading condition considering the ongoing growth of urban environment.

Table 4: The summary of the best and worst design scenarios under three shading conditions.

<table>
<thead>
<tr>
<th>Shading condition</th>
<th>Parameter</th>
<th>Best design</th>
<th>Worst design</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Design scenario</td>
<td>Value</td>
<td>Design scenario</td>
<td>Value</td>
</tr>
<tr>
<td>7%</td>
<td>NPV after 25 years</td>
<td>B0+A0</td>
<td>122665</td>
<td>B0+A340</td>
</tr>
<tr>
<td></td>
<td>NPV per kW of system</td>
<td>B340+A20</td>
<td>2290</td>
<td>B340+A340</td>
</tr>
<tr>
<td></td>
<td>Payback Period (years)</td>
<td>-</td>
<td>11</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Self-consumption ratio</td>
<td>B340+A20</td>
<td>90.24%</td>
<td>B0+A0</td>
</tr>
<tr>
<td>19%</td>
<td>NPV after 25 years</td>
<td>B0+A0</td>
<td>93607</td>
<td>B0+A340</td>
</tr>
<tr>
<td></td>
<td>NPV per kW of system</td>
<td>B340+A10</td>
<td>1737</td>
<td>B340+A340</td>
</tr>
<tr>
<td></td>
<td>Payback Period (years)</td>
<td>B0+A10</td>
<td>12</td>
<td>Rest scenarios</td>
</tr>
<tr>
<td></td>
<td>Self-consumption ratio</td>
<td>B340+A20</td>
<td>94.07%</td>
<td>B0+A0</td>
</tr>
<tr>
<td>25%</td>
<td>NPV after 25 years</td>
<td>B0+A0</td>
<td>78544</td>
<td>B0+A340</td>
</tr>
<tr>
<td></td>
<td>NPV per kW of system</td>
<td>B340+A10</td>
<td>1455</td>
<td>B340+A340</td>
</tr>
<tr>
<td></td>
<td>Payback Period (years)</td>
<td>-</td>
<td>14</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Self-consumption ratio</td>
<td>B340+A20</td>
<td>95.29%</td>
<td>B0+A0</td>
</tr>
</tbody>
</table>

3.2 The maximum shading loss

In this study, the maximum annual shading loss that makes the NPV become zero is identified as shown in Figure 4. The maximum shading loss varies from 54% to 56%. The B0+A10, B10+A10 and B340+A10 are the best designs to sustain the shading loss while B0+A340, B10+A340 and B340+340 are the worst. Although the scenario B0+A0, B10+A0 and B340+A0 have the largest panel area and the greatest system capacity, they do not perform the best when coping with the shading loss. The high solar irradiation instead of the large panel area makes the system sustain more shading. When the PV azimuth angle is 10 degrees, the annual solar irradiation is 1,753 kW/m², which is the greatest among all five azimuth angles in this study (NREL, 2018). The result indicates the optimal azimuth angle is the critical factor to deal with the shading loss instead of the building orientation which affects the available space for the system.

![Maximum shading loss](image)

Figure 4: The maximum annual shading loss of all the design scenarios.
4. CONCLUSION

The study investigates the rooftop PV design for urban areas that may face increasing overshadowing with an emphasis on the economic performance, using a case study located in the urban area of Melbourne, Australia. Shading effect, building orientation, and azimuth angle of PV system are considered when designing the rooftop PV system in the urban environment. The results of the study provide an insight for the best and worst designs of the rooftop PV system in urban areas of Melbourne. The main findings of the study are as follows:

- Under all three shading conditions, the scenario B0+A0 has the best NPV while B0+A340 has the worst. The combination of B340+A10 can provide higher economic benefit per kW than other scenarios.
- There is a 3-year delay in terms of payback year when the shading loss increases from 7% to 25%.
- The maximum of the shading loss varies from 54% to 56%. Regardless of the building orientation, the azimuth angle of 10 degrees towards east can help the PV system sustain more shading loss.

Based on the findings, recommendations are generated for the rooftop PV system design covering most urban areas of Melbourne at the risk of shading effect. For buildings facing north, the rooftop PV system should also be oriented north to achieve the best economic performance. If the building orientation is 20 degrees counter-clockwise from true north, the recommended azimuth angle of the PV system is 10 degrees towards east. In order to enhance the ability to sustain shading loss, the azimuth angle of PV system is suggested also to be 10 degrees towards east.

References


Horn, B. (2011) Maximizing performance: Determining the relative influence of key design elements on the performance of grid connected photovoltaic systems in Geraldton, Western Australia, Murdoch University.


