School of Civil and Mechanical Engineering

Renewable Energy Principles (ELEN3004)

Semester 2 2022

Associate Professor Sumedha Rajakaruna

Evaluation of Economic Performance of a Grid-Connected Roof-Top PV Array

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Problem 1

a)

Table 1.1 Table of Parameters and Values

Parameter	Symbol	Value	Units
Hour angle	H	+90	° (degrees)
Day number	n	1	Days
Latitude angle	L	-26.5	° (degrees)
Solar altitude angle	β	10.0453	° (degrees)
Solar declination angle	δ	-23.0116	° (degrees)
Solar azimuth angle	$Φ_s$	110.8122	° (degrees)
Sunrise time	-	05:11:06	hh:mm:ss
Sunrise time	-	18:48:54	hh:mm:ss
Daylight period	-	13:37:48	hh:mm:ss

Solar declination angle calculation

$$\delta = 23.45\sin\left[\frac{360}{365}(n-81)\right] \qquad \text{Equation 1.1}$$

$$\delta = 23.45\sin\left[\frac{360}{365}(1-81)\right]$$

$$\delta = -23.0116°$$

Hour angle calculation

$$H = \frac{15°}{hr} \times (\text{hours before solar noon}) \qquad \text{Equation 1.2}$$

$$H = 15° \text{ x } 6$$

$$H = 90°$$

Solar altitude angle calculation

$$sin\beta = \cos(L)\cos(\delta)\cos(H) + \sin(L)\sin(\delta) \qquad \text{Equation 1.3}$$

$$sin\beta = \cos(-26.5°)\cos(-23.0116°)\cos(90°) + \sin(-26.5°)\sin(-23.0116°)$$

$$\beta = 10.0453°$$

Solar azimuth angle calculation

$$\sin(\Phi s) = \frac{\cos(\delta)\sin(H)}{\cos(\beta)} \qquad \text{Equation 1.4}$$

$$\sin(\Phi s) = \frac{\cos(-23.0116°)\sin(90°)}{\cos(10.0453°)}$$

$$\phi_s = 69.188°, 110.8122°$$

Solar azimuth angle inequality check

$$\text{If } \cos(H) \geq \frac{\tan(\delta)}{\tan(L)} \text{ } then\ |\phi_s| \leq 90°, \text{otherwise } |\phi_s| > 90° \qquad \text{Equation 1.5}$$

$$\cos(90°) < \frac{\tan(-23.0116°)}{\tan(-26.5°)} \therefore |\phi_s| > 90° \therefore \phi_s = 110.8122° \text{ East of North}$$

Sunrise/sunset hour angle, time and daylight period calculations

$$\mathrm{B} = 0 \;\therefore \cos(\mathrm{H}) = -\tan(\mathrm{L})\tan(\delta)$$ Equation 1.6

$$\cos(\mathrm{H}) = -\tan(-26.5°)\tan(-23.0116°)$$

$$\mathrm{H} = \pm 102.2249°$$

$$Therefore\ sunrise/sunset\ times = 12hrs \pm \left(\frac{102.2249°}{15°}\right) hrs$$ (Refer to Equation 1.2)

$$Sunrise\ time = 05{:}11{:}06\ hrs$$

$$Sunset\ time = 18{:}48{:}54\ hrs$$

$$Total\ daylight\ period = 18{:}48{:}54\ hrs - 05{:}11{:}06\ hrs$$

(Note: these are solar times)

$$Total\ daylight\ period = 13{:}37{:}48\ hrs$$

b)

Table 1.2 Table of Sunrise/Sunset Times on the 21st of Each Month

Month	Sunrise Time	Sunset Time
January	05:17:52	18:42:08
February	05:37:17	18:22:43
March	05:59:12	18:00:48
April	06:23:27	17:36:33
May	06:42:08	17:17:52
June	06:49:58	17:10:02
July	06:42:50	17:17:10
August	06:23:49	17:36:11
September	05:59:36	18:00:24
October	05:36:11	18:23:49
November	05:17:10	18:42:50
December	05:10:02	18:49:58

Note: Refer to equations 1.1 and 1.6 for calculating values in Table 1.2.

c)

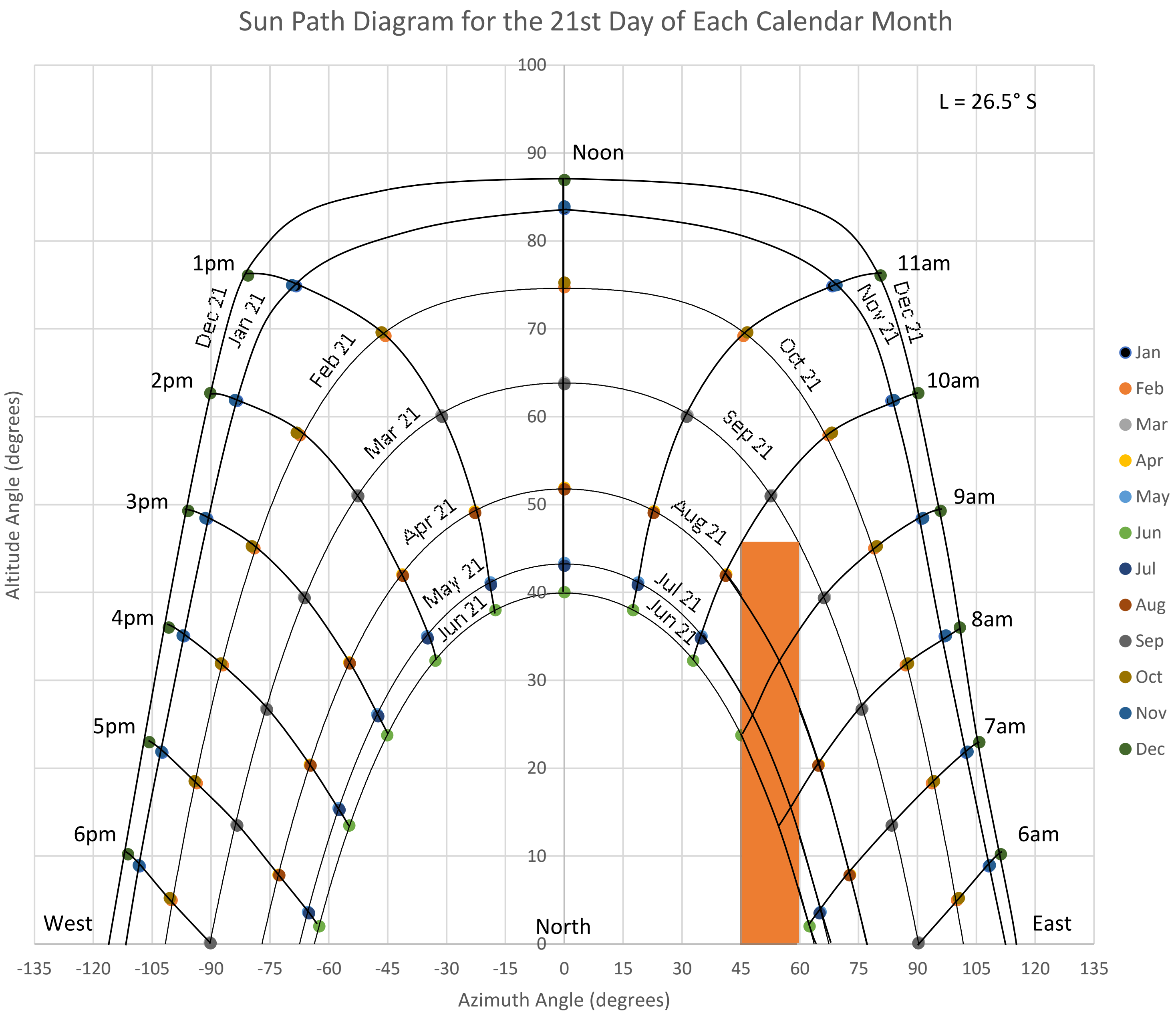

Figure 1 Sun Path Diagram for the 21st Day of Each Calendar Month

From Figure 1 shown above, the shading effect of the obstruction is such that the site is shaded from approximately 7:20am until just after 9am in June, 7:40am until 9:15am in May and July, and 8:30am until 9:45am in April and August. It is possible that there are a brief couple of minutes where the site is shaded at approximately 9:30am in March and September.

Problem 2

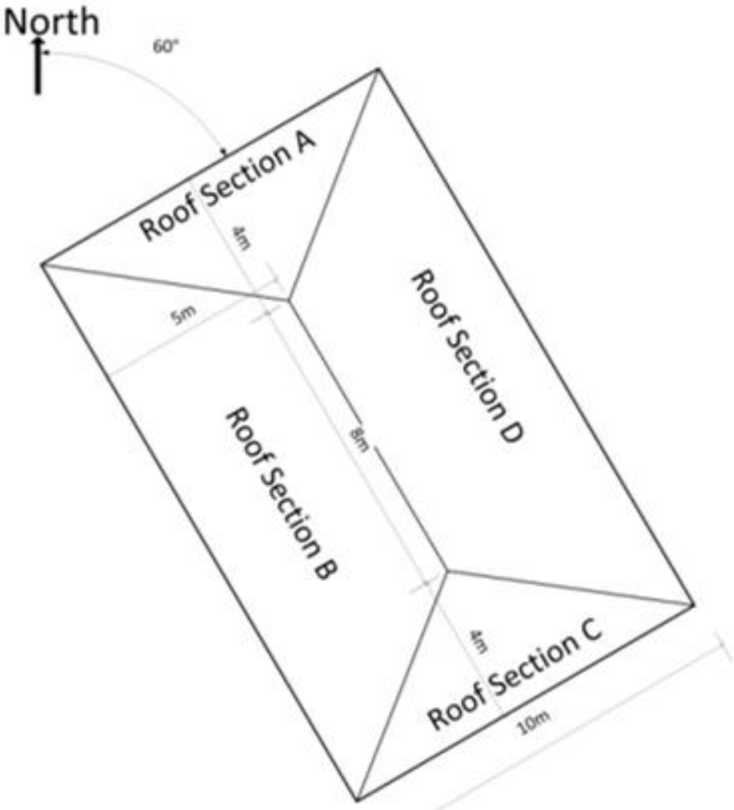

Figure 2 Site Plan View of Roof [2]

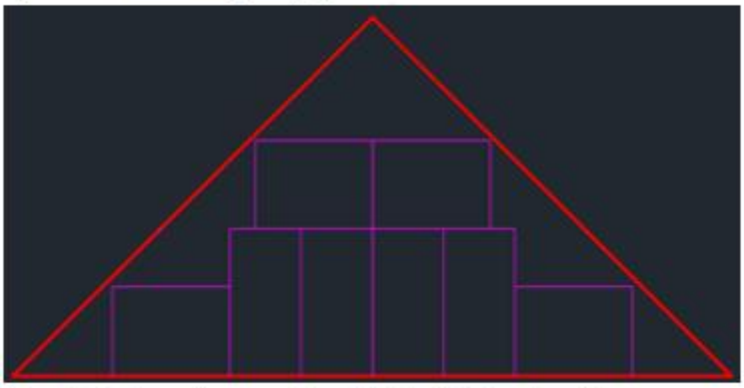

Figure 3 Maximum Number of Panels In Roof Sections A and C

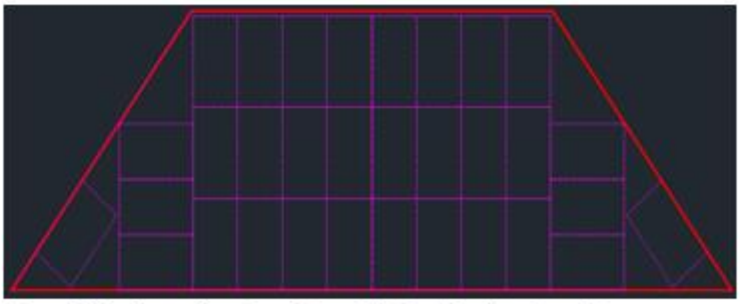

Figure 4 Maximum Number of Panels in Roof Sections B and D

a)

From Figure 2 shown at left the four roof sections A, B, C and D are respectively 20m^2, 60m^2, 20m^2, and 60m^2. The area of a single PV cell to be used is 1.623m^2 with dimensions 1636mm x 992mm x 45mm [1]. Given that no cells may overhang any section of the roof, the maximum number of cells in roof sections A and C, and B and D can be seen in figures 3 and 4 shown at left as being 8 and 32 respectively.

There are other orientations of cells that can be employed, but those shown at left show the maximum numbers of cells per roof section, and these orientations were chosen over other orientations primarily due to easier installation as there are fewer obscure angles of panel orientation i.e., they are primarily orthogonally oriented.

Given the number of cells per roof section, their corresponding total area, and the area of the roof sections this results in an area utilisation rate of 64.92% for roof sections A and C, and 86.56% for roof sections B and D.

Note that these values were generated under the assumption that the panels shall all be placed flat against their respective roof sections i.e., there is no relative panel tilt thus there is no separation between rows of collectors. Further to this, this layout does not account for any tolerances of dimensions or thermal expansion and assumes that all panels will be placed with no space between them. 12 solar PV modules are required to be installed to meet the 3kW STC rated power requirement of the array due to their STC rated max power output of 250W [1].

b)

Firstly, the site is located at a latitude South of the equator that lies outside of the region between the Tropics of Capricorn and Cancer. This means that the sun will always be in the Northern sky at the site throughout the year. From the site plan in Figure 2, roof section A is facing 30 degrees West of North, roof section B is facing 120 degrees West of North, roof section C is facing 150 degrees East of North and roof section D is facing 60 degrees East of North. From this information, it is reasonable to expect that roof sections A and D will receive most of the annual solar insolation per square meter while roof sections B and C will receive less as they are on the Southern side of the site. Further to this, roof section A should be expected to be exposed to more intense solar insolation per square meter due to its azimuth angle of 30 degrees West of North, which means it is orthogonally oriented towards the sun just before 2pm as shown in Figure 1. This time of day typically yields higher solar insolation levels than what roof section D is exposed to at its angle of 60 degrees East of North, orthogonally oriented towards the sun at 9:30am. Further to this, roof section D is shaded at the time it is orthogonally oriented towards the sun for almost half of the year.

Roof section B will only experience direct insolation in the late afternoon/early evening in Summer and roof section C will never experience directly orthogonal sunlight and will only ever be exposed to reduced insolation at a non-orthogonal angle to the roof section at sunrise. It can be expected that the order of highest to lowest annual insolation per square meter for the roof sections is A, D, B, C.

c)

While roof section D is expected to experience less annual solar insolation per square meter than roof section A due to its azimuth angle and the shading effect of the obstruction, it should still be selected for the PV array installation. The reason for this is that roof section A can only provide area for 8 solar PV modules (at 250W rated max power STC each) without overhanging any section of the roof yielding only 2kW maximum rated power at STC. This does not meet the requirement of 3kW STC power output for the PV array installation. Roof section D, on the other hand, has enough area for four times the number of solar PV modules as roof section A, giving it a maximum possible rated power output of 8kW at STC. Hence, roof section D should be selected for the PV array installation.

Problem 3

Table 3.1 Table of Parameters and Values

Parameter	Symbol	Value	Units
Apparent extra-terrestrial flux	A	1235	W/m^2
Optical depth	k	0.1393	-
Air mass ratio	m	1.1264	-
Beam radiation	I_B	1235	W/m^2
Collector tilt angle	Σ	22	° (degrees)
Collector azimuth angle	ϕ_C	60	° (degrees)
Angle of incidence	θ	13.2106	° (degrees)
Direct beam radiation on collector	I_{BC}	1027.71	W/m^2
Sky diffuse factor	C	0.1	-
Diffuse radiation on collector	I_{DC}	101.72	W/m^2
Reflected radiation on collector	I_{RC}	0	W/m^2
Total radiation on collector	I_C	1129.43	W/m^2

Apparent extra-terrestrial flux calculation

$$A = 1160 + 75\sin\left[\tfrac{360}{365}(n - 275)\right] \quad \text{Equation 3.1}$$

$$A = 1160 + 75\sin\left[\frac{360}{365}(1 - 275)\right]$$

$$A = 1235\frac{W}{m^2}$$

Optical depth calculation

$$k = 0.174 + 0.035\sin\left[\tfrac{360}{365}(n - 100)\right] \quad \text{Equation 3.2}$$

$$k = 0.174 + 0.035\sin\left[\frac{360}{365}(1 - 100)\right]$$

$$k = 0.1393$$

Air mass ratio calculation (NOTE: Refer to equations 1.1, 1.2 and 1.3 for solar declination angle, hour angle and altitude angle respectively)

$$m = \tfrac{1}{\sin(\beta)} \quad \text{Equation 3.3}$$

$$m = \frac{1}{\sin(62.5967°)}$$

$$m = 1.1264$$

Beam of radiation attenuation calculation

$$I_B = Ae^{-km} \quad \text{Equation 3.4}$$

$$I_B = 1235e^{-0.1393\times1.1264}$$

$$I_B = 1055.65\frac{W}{m^2}$$

Angle of incidence on collector calculation (NOTE: Refer to equation 1.4 for solar azimuth angle)

$$\cos(\theta) = \cos(\beta)\cos(\phi_s - \phi_c)\sin(\Sigma) + \sin(\beta)\cos(\Sigma) \quad \text{Equation 3.5}$$

$$\cos(\theta) = \cos(62.5967°)\cos(89.2750° - 60°)\sin(22°) + \sin(62.5967°)\cos(22°)$$

$$\theta = 13.2106°$$

Direct beam radiation on collector calculation

$$I_{BC} = I_B cos\theta \quad \text{Equation 3.6}$$

$$I_{BC} = 1055.65 \times \cos(13.2106°)$$

$$I_{BC} = 1027.71\frac{W}{m^2}$$

Diffuse radiation on collector calculation

$$I_{DC} = CI_B\left(\tfrac{1+cos\Sigma}{2}\right) \quad \text{Equation 3.7}$$

$$I_{DC} = 0.1 \times 1055.65 \times \left(\frac{1 + \cos(22°)}{2}\right)$$

$$I_{DC} = 101.72\frac{W}{m^2}$$

Total incident radiation on collector calculation

NOTE: The reflected radiation is assumed to be zero.

$$I_C = I_{BC} + I_{DC} + I_{RC} \quad \text{Equation 3.8}$$

$$I_C = 1027.71 + 101.72 + 0$$

$$I_C = 1129.43 \frac{W}{m^2}$$

Problem 4

a)

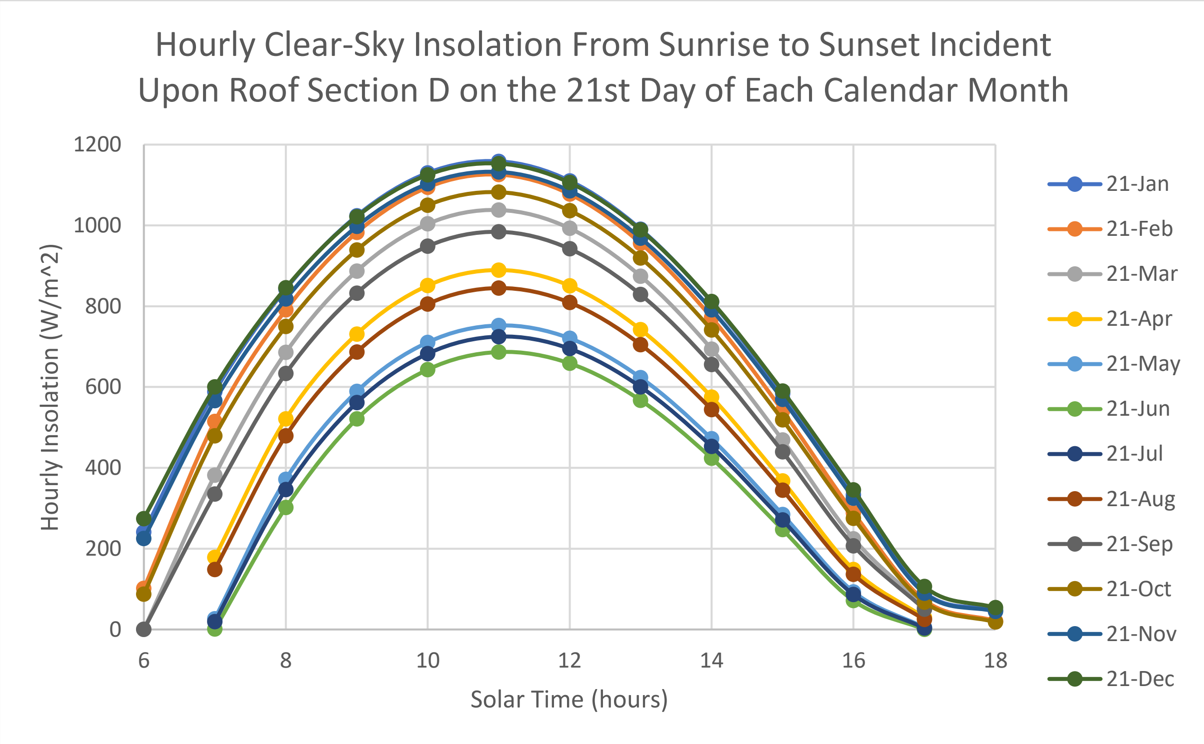

Figure 5 Clear-Sky Hourly Insolation from Sunrise to Sunset Incident on Roof Section D on the 21st of Each Month NOTE: This does not account for the insolation loss due to the shading effect of the obstruction. See part b) for insolation loss.

b)

As found earlier from Figure 1, in the month of June, the roof section is shaded (hence it is assumed to receive zero insolation) from 7:20am to 9am which corresponds to 16.66% of the insolation from 6:30am to 7:30am which is assumed to be constant and equal to the insolation at 7am, however it can be neglected as the level of insolation is so low at this time. 100% of the insolation from 7:31am to 8:30am, and 50% of the insolation from 8:31am to 9:30am is obstructed during June. In the months of May and July, the roof section is shaded from 7:40am to 9:15am which corresponds to 83.33% of the insolation from 7:30am to 8:30am, and 75% of the insolation from 8:31am to 9:30am. In the months of April and August the roof section is shaded from 8:30am to 9:45am which corresponds to 100% of the insolation from 8:30am to 9:30am and 25% of the insolation from 9:31am to 10:30am. In the months of March and September there appears to be a very brief period of shading at 9:30am. Assuming that this period lasts 5 minutes this corresponds to 8.33% which can be considered to be negligible. Assume, for the calculations below, that the insolation of the 21st day of each month represents the insolation of all days in that month.

Expected loss of insolation in each day of June calculation

$$I_{Loss} = 100\% \times I_{8am} + 50\% \times I_{9am} \qquad \text{Equation 4.1.0}$$

$$I_{Loss} = 1 \times 301.54 + 0.5 \times 520.83$$

$$I_{Loss} = 561.96\,\frac{W}{m^2}$$

Expected loss of insolation in each day of May calculation

$$I_{Loss} = 83.33\% \times I_{8am} + 75\% \times I_{9am} \qquad \text{Equation 4.1.1}$$

$$I_{Loss} = 0.8333 \times 371.75 + 0.75 \times 588.89$$

$$I_{Loss} = 751.45\,\frac{W}{m^2}$$

Expected loss of insolation in each day of July calculation

$$I_{Loss} = 83.33\% \times I_{8am} + 75\% \times I_{9am} \qquad \text{Equation 4.1.2}$$

$$I_{Loss} = 0.8333 \times 346.29 + 0.75 \times 561.31$$

$$I_{Loss} = 709.55\,\frac{W}{m^2}$$

Expected loss of insolation in each day of April calculation

$$I_{Loss} = 100\% \times I_{9am} + 25\% \times I_{10am} \qquad \text{Equation 4.1.3}$$

$$I_{Loss} = 1 \times 731.23 + 0.25 \times 851.19$$

$$I_{Loss} = 944.03\,\frac{W}{m^2}$$

Expected loss of insolation in each day of August calculation

$$I_{Loss} = 100\% \times I_{9am} + 25\% \times I_{10am} \qquad \text{Equation 4.1.4}$$

$$I_{Loss} = 1 \times 686.47 + 0.25 \times 805.69$$

$$I_{Loss} = 887.89\,\frac{W}{m^2}$$

c)

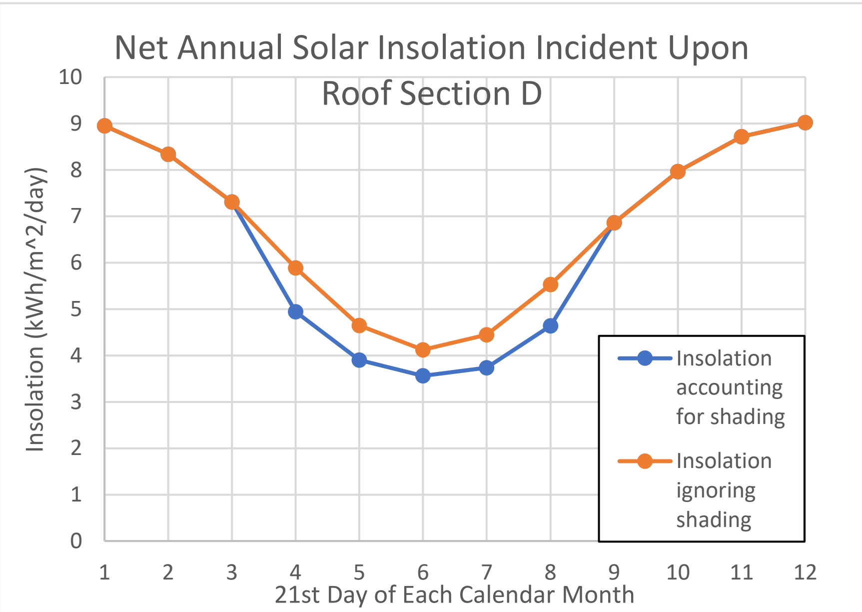

Figure 6 Net Annual Solar Insolation Incident Upon Roof Section D Showing the Expected Net Insolation with and Without the Shading Effect of the Obstruction

The net annual insolation considering the shading effect of the obstruction is 6.495 kWh/m^2/day which comes to 2,370.62 kWh/m^2/year

The net annual insolation ignoring the shading effect of the obstruction is 6.816 kWh/m^2/day which comes to 2,487.88 kWh/m^2/year.

Problem 5

a)

Average annual electrical energy produced by a 12 solar PV module array in kWh on roof section D

$$E_{generated} = \eta_{\text{clouds}} \cdot \eta_{PV} \cdot \eta_{inverter} \cdot E_{annual} \cdot A_{array} \qquad \text{Equation 5.1}$$

$$E_{generated} = 0.9 \cdot 0.15 \cdot 0.95 \cdot 2{,}370.62 \cdot (12 \times 1.623)$$

$$E_{generated} = 5{,}921.33\ kWh/year$$

b)

Capital cost for the installation of a 12 solar PV module 3kW STC array system

$$C_{initial} = (1 + GST) \cdot \left(C_{panels} + C_{inverter} + C_{frames} + C_{installation}\right) - C_{rebate} \qquad \text{Equation 5.2}$$

$$C_{initial} = (1 + 0.1) \cdot (12 \times \$225 + \$950 + \$750 + \$1650) - \$2{,}331$$

$$C_{initial} = \$4{,}324$$

Annual maintenance cost of a 12 solar PV module 3kW PV array system

$$C_{maintenance} = 0.05 \times C_{initial} \qquad \text{Equation 5.3}$$

$$C_{maintenance} = 0.05 \times \$4{,}324$$

$$C_{maintenance} = \$216.20$$

Average annual revenue from power generation being fed into the grid

$$R_{annual} = 0.4 \times E_{generated} \cdot I_{utility} \qquad \text{Equation 5.4}$$

$$R_{annual} = 0.4 \times \frac{5{,}921.33\ kWh}{year} \cdot \frac{\$0.03}{kWh}$$

$$R_{annual} = \$71.06$$

Average annual energy bill savings

$$S_{annual} = 0.6 \times E_{generated} \cdot C_{utility} \qquad \text{Equation 5.5}$$

$$S_{annual} = 0.6 \times 5{,}921.33 \frac{kWh}{year} \cdot \frac{\$0.2933}{kWh}$$

$$S_{annual} = \$1{,}042.04$$

Simple payback period

$$Payback\ Period = \frac{C_{initial}}{R_{annual} + S_{annual} - C_{maintenance}} \qquad \text{Equation 5.6}$$

$$Payback\ Period = \frac{\$4{,}324}{\$71.06 + \$1{,}042.04 - \$216.20}$$

$$Payback\ Period = 4.821\ years$$

c)

Profit after 25 years

$$Profit = 25 \cdot (S_{annual} + R_{annual} - C_{maintenance}) - C_{initial} \qquad \text{Equation 5.6}$$

$$Profit = 25 \cdot (\$1{,}042.04 + \$71.06 - \$216.20) - \$4{,}324$$

$$Profit = \$18{,}098.50$$

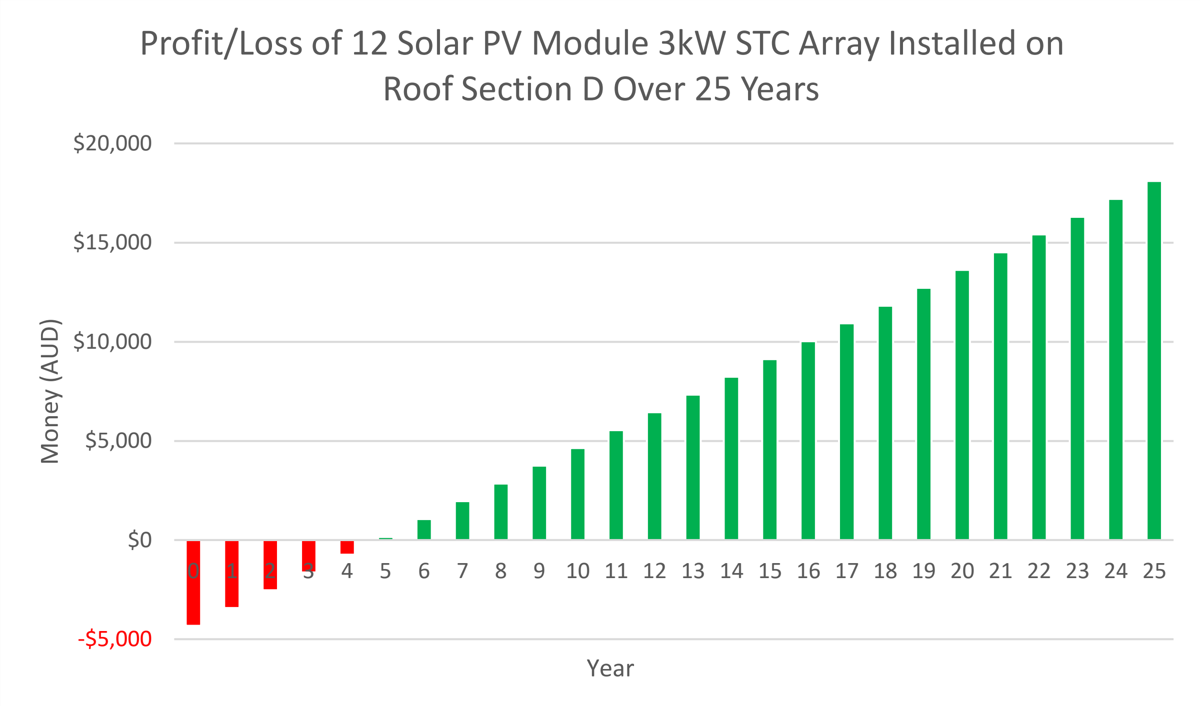

Figure 7 Profit/Loss Chart of 12 Panel 3kW STC Array Installed on Roof Section D Over 25 Years NOTE: The profit shown here is cumulative profit over the 25-year period.

d)

Profit after 25 years ignoring the shading effect of the obstruction

$$Profit = 25 \cdot (\$1{,}093.58 + \$74.57 - \$216.20) - \$4{,}324 \qquad \text{From Equation 5.6}$$

$$Profit = \$19{,}474.75$$

Loss of income due to the shading effect of the obstruction over 25 years

$$Loss\ of\ Income = \$19{,}474.75 - \$18{,}098.50 \qquad \text{Equation 5.7}$$

$$Loss\ of\ Income = \$1{,}376.25$$

NOTE: These calculations omit the effect of accounting for scrap value at the end of the asset's life and degradation in performance of the PV cells over time.

References

[1] Hareon Solar Technology Co., Ltd., "3BB HR-230P-18/Bb-HR-250P-18/Bb Poly-Crystalline Silicon Module," [Online]. Available: https://www.sicleanenergy.com.au/wp-content/uploads/2014/06/3BBHR-230P-18-Bb-HR-250P-18-Bb.pdf. [Accessed 21 August 2022].

[2] S. Rajakaruna, "Evaluation of Economic Performance of a Grid-Connected Roof-Top PV Array," 2 September 2022. [Online]. Available: https://learn-ap-southeast-2-prod-fleet01-xythos.content.blackboardcdn.com/5dc3e34515a0e/16975939?X-Blackboard-Expiration=1661104800000&X-Blackboard-Signature=RpM9oP3NUzHNKQ2%2BEthVTMPs4C08pEH7JaOW4oVCV%2BQ%3D&X-Blackboard-Client-Id=305909&response-cache-. [Accessed 21 August 2022].