ELEN3004 – RENEWABLE ENERGY PRINCIPLES

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

Semester 1, 2022

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Executive Summary

This document aims to design a 3kW STC rated grid-connected photo-voltaic (PV) array as a roof-top installation for a shed in Meekatharra through a physical and financial analysis. This report is intended to be read alongside the assignment brief (the brief is attached in section 5 Appendix 1: Assignment Brief); for further information on the design proposal see said assignment brief.

As the report is intended to be read alongside the assignment brief, the report has been structured the correlate with the questions given in the brief. The body of the report pertains to the Assignment Problem and therefore has been broken into the questions given; thus, section 2.2.a of this report corresponds to question 2 (a) of the Assignment Problem given in the assignment brief (see section 5 Appendix 1: Assignment Brief).

Given the nature of many of the calculations and the need to graph results, Microsoft Excel has been used to produce several of the results. The excel file used to produce said results has been supplied alongside this document.

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1. Introduction

The aim of this assignment is to design a 3kW STC rated grid-connected photo-voltaic (PV) array and to analyse the physical and financial situation surrounding it. The PV array is to be installed on a roof on a shed near Meekatharra with latitude 26.5^0 South. The following section pertains to the questions given in the Assignment Problems section of the assignment brief (see section 5 Appendix 1: Assignment Brief).

2. Assignment Problem

2.1.

2.1.a

Sample calculations for the sun's position angles at 6am solar time on 1st January:

$$n = 1\,, L = \; -26.5$$

$$\delta = 23.45 \sin\frac{360}{365}(1-80)$$
$$= \; -23.01$$

$$H = 15 * 6$$
$$= 90$$

$$Therefore, \sin\beta \; = \cos L \cos\delta \cos H + \sin L \sin\delta$$
$$= \; \cos(-26.5)\cos(-23.01)\cos 90 + \sin(-26.5)\sin(-23.01)$$
$$= \; 0.174$$

$$Thus, altitude\ angle: \beta \; = \mathbf{10.02°}$$

$$\sin\Phi = \frac{\cos\delta\sin H}{\cos\beta}$$
$$= \frac{\cos(-23.01)\sin 90}{\cos 10.02}$$
$$= 0.935$$

$$Thus, Azimuth\ angle: \Phi \; = \mathbf{69.18°}$$

To determine period of daylight on the 1st of January we calculate the sunrise and sunset:

$$\cos H = -\tan L \tan\delta$$
$$= \; -\tan(-26.5)\tan(-23.01)$$
$$= \; -0.212$$

$$Therefore, \qquad H = \; \pm 102.22$$
$$Sunrise: \frac{102.22}{15} = 6.81$$
$$The\ sun\ rises\ at\ 5{:}12am$$
$$Sunset: \frac{-102.22}{15} = -6.81$$
$$The\ sun\ sets\ at\ 6{:}49pm$$

Thus, the period of daylight on the 1st of January is **13 hours and 37 mins** long.

2.1.b

Sunrise and sunset times on the 21st of each month of the year:

Month	Sunrise	Sunset
Jan	5:17	18:42
Feb	5:37	18:22
Mar	5:59	18:00
Apr	6:23	17:36
May	6:42	17:17
Jun	6:49	17:10
Jul	6:42	17:17
Aug	6:23	17:36
Sep	5:59	18:00
Oct	5:36	18:23
Nov	5:17	18:42
Dec	5:10	18:49

[The full table and calculations used to acquire these results can be found in *Sheet 1* of the assignments accompanying excel file.]

2.1.c

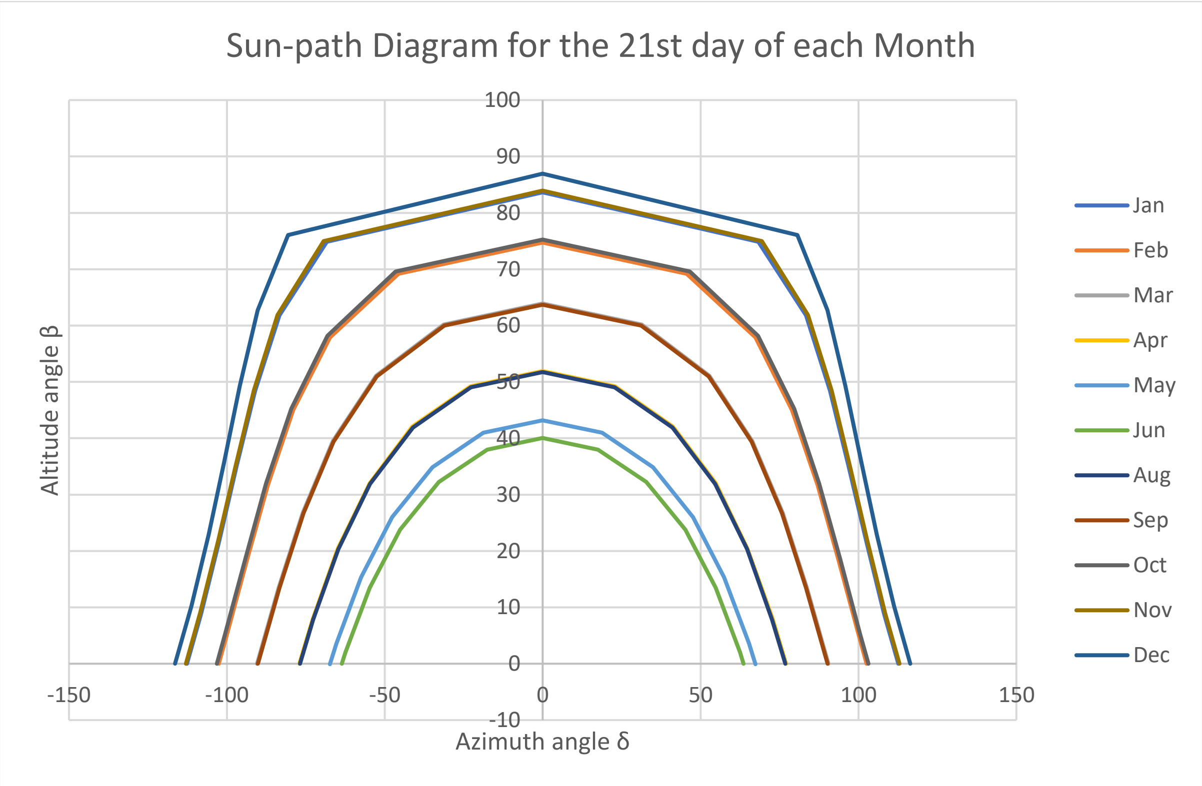


Figure 1 - Sun-path diagram for 21st day of each month

[The full table and calculations used to acquire these results can be found in *Sheet 2* of the assignments accompanying excel file.]

2.1.d

The following diagram shows the obstruction that could cause a shadow on site:

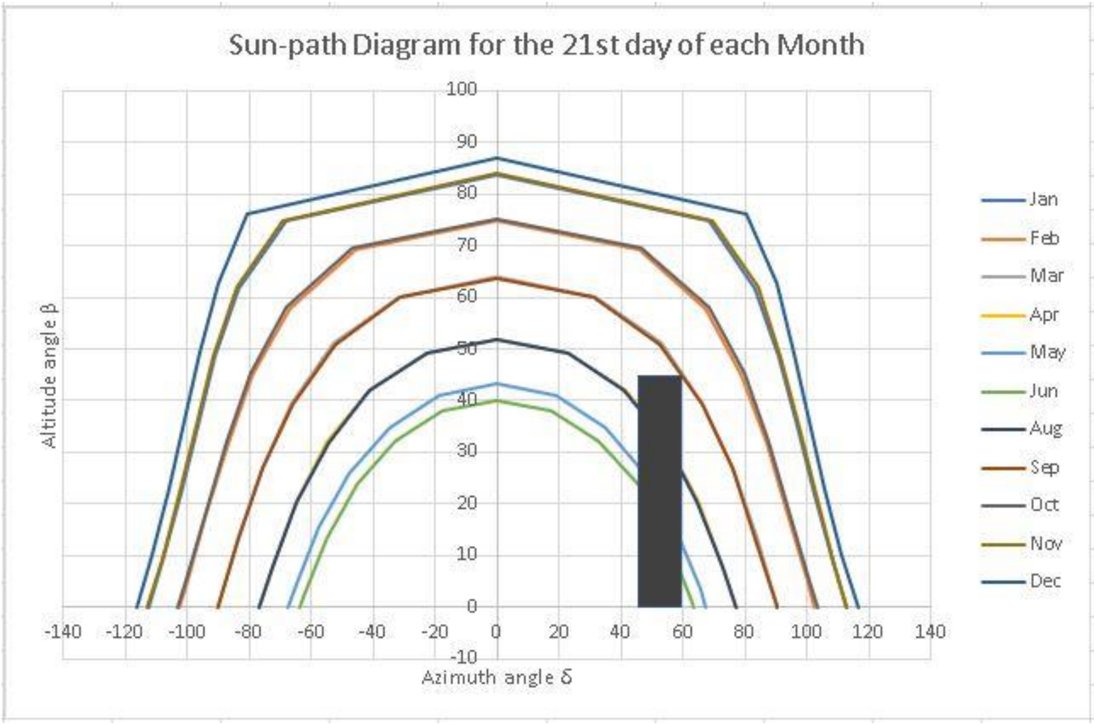


Figure 2 - Sun-path diagram for 21st day of each Month

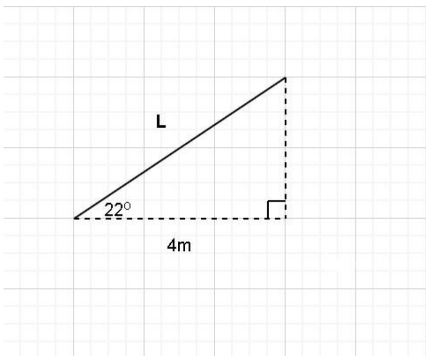
Hours of shadowing in obstructed months: 9 to 10amin May (**1 hr**); 7:30 to 9am in June (**1:30 hrs**); 8:30 to 9:30am in August (**1 hr**).

2.2.

2.2.a

In this section, the maximum number of (1636x992) mm solar PV modules that can fit into each section of the roof (see roof diagram in Appendix 1 – Assignment Brief), will be represented graphically using Sketchup. Given the symmetry of the roof, sections A and C can be paired together, as can sections B and D. The first step to graphically representing sections A/C and B/D is to establish the dimensions of the sections shape, being a triangle and a trapezium, respectively; the following calculations were made to find their dimensions (assuming both roof sections A/C and B/D have an incline of 22^{O}):

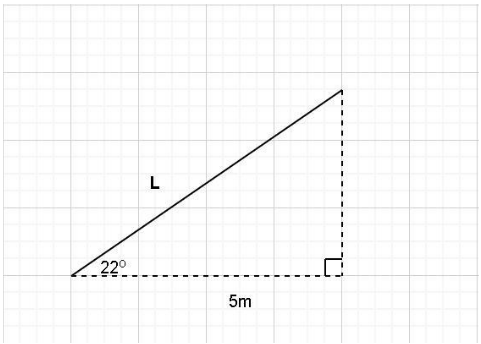
Sections A/C: (note: not to scale)



Where L is the length of the surface of the roof, therefore:

$$L = \frac{4}{\cos 22°} = 4.314m$$

Sections B/D: (note: not to scale)



Where L is the length of the surface of the roof, therefore:

$$L = \frac{5}{\cos 22°} = 5.393m$$

Next, we can graphically represent our pairs of roof sections and superimpose as many (1636x992) mm rectangles as we can to determine the maximum number of solar PV modules able to fit on that section of the roof. To comply with real-world standards a 10mm gap is left between each PV array and the edges of the roof section and, as stated by "Crystalline Silicon PV Modules Installation Manual (IEC Version) (n.d.), a recommended 30mm of space is left between neighbouring PV modules to account for "forces generated during thermal expansion and contraction of the supporting rail may influence the performance and use of the module". Thus, the resulting maximum solar PV modules for each section are shown graphically below:

Sections A/C:

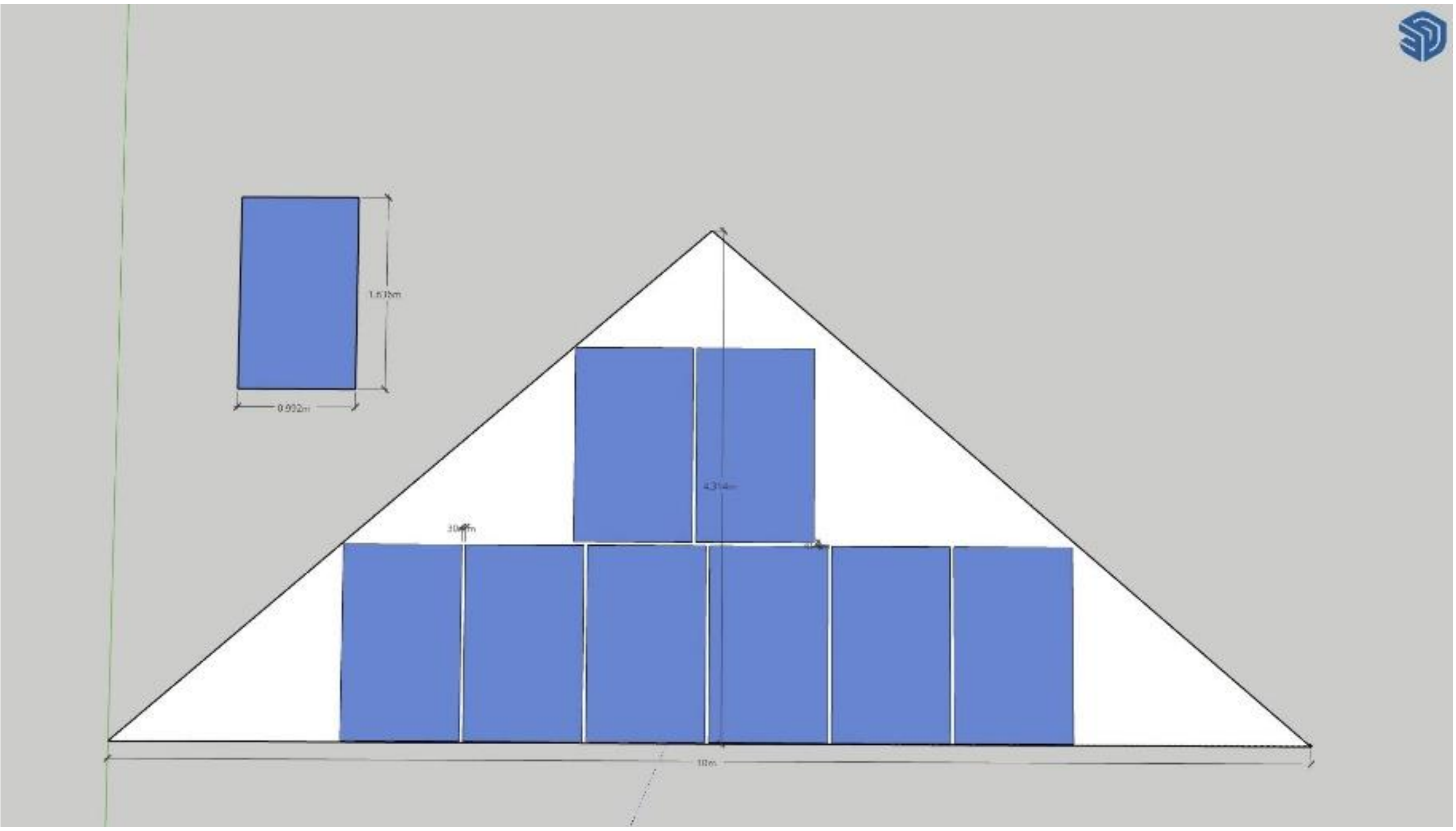


Figure 3 - roof section A/C in Sketchup

Maximum solar PV modules for sections A and C is **8** modules.

Sections B/D:

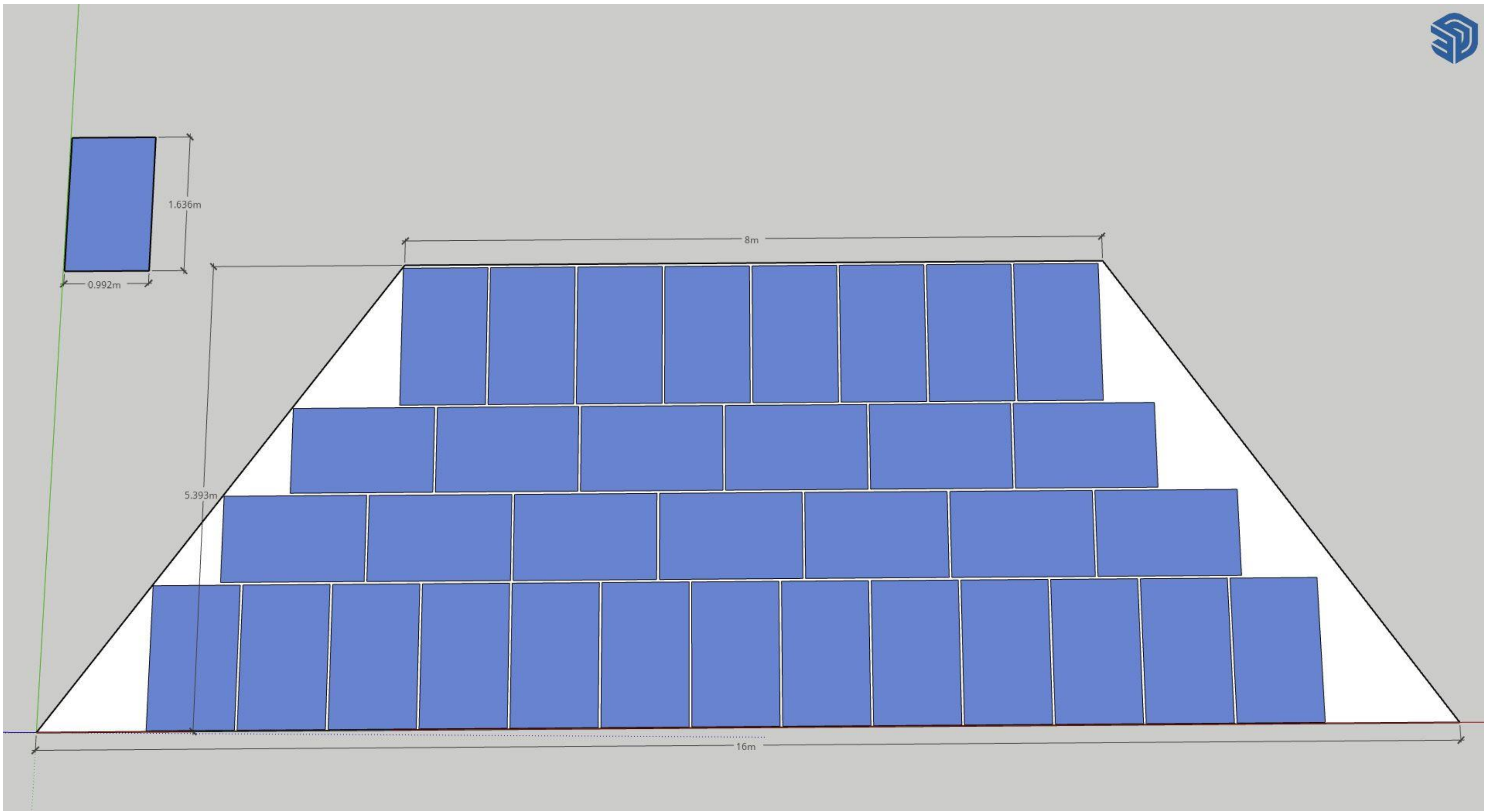


Figure 4 - roof section B/D in Sketchup

Maximum solar PV modules for sections B and D is **34** modules.

2.2.b

As stated by "Solar Panel Orientation - Energy Education" (n.d.), it is preferable to have solar panels point due North in the southern hemisphere. The only other consideration made when determining which of the roof sections (see roof diagram in Appendix 1 – Assignment Brief) receive the highest annual insolation per square meters would be the sheer square meters of solar panel available on each section; comparing the sections:

Sections A/C:

$$Area = 8 * 1.636 * 0.992 = 12.983\ m^2$$

Sections B/D:

$$Area = 34 * \ 1.636 * 0.992 = 55.17\ m^2$$

Considering roof sections B and D are over four times the area of roof sections A and C and the fact that solar panels should be orientated towards true North we can establish the following list (from highest annual insolation to lowest):

1. Section D
2. Section A
3. Section B

4. Section C

2.2.c

Based on the work done in section 2.2.a and section 2.2.b we are able to determine the suitable roof section to install the solar PV array; sharing the maximum amount of PV modules and having the suspected highest annual insolation, section D of the roof would be best suited for the installation of the solar PV array.

2.3.

Sample calculations for the total insolation on roof section D's collector at 10amsolar time on January 1st:

$$C = 0.01, \qquad \Phi c = 60°, \qquad \Sigma = 22°$$

$$From\ section\ 2.1.a, \qquad \delta = -23.01$$
$$H = 2\ .\ 15 = 60$$

$$\sin\beta = \cos(-26.5)\cos(-23.01)\cos 30 + \sin(-26.5)\sin(-23.01)$$
$$Therefore, \beta = 62.6°$$

$$\sin\Phi = \frac{\cos(-23.01)\sin 30}{\cos 62.6}$$
$$Therefore, \Phi = 89.27°$$

$$I_B = Ae^{-k.m}$$

$$A = 1160 + 75\sin\left(\frac{360}{365}(1-275)\right) = 1235$$

$$k = 0.174 + 0.035\sin\left(\frac{360}{365}(1-100)\right) = 0.1393$$

$$m = \frac{1}{\sin 62.5964} = 1.1264$$

$$Finally, \qquad I_C = I_B\left(\cos\theta + C\left(\frac{1+\cos\Sigma}{2}\right)\right)$$

$$= 1235e^{(-0.1393)(1.1264)}\left(0.934627 + (0.1)\left(\frac{1+\cos 22}{2}\right)\right)$$

$$= \mathbf{1088.4}\ W/m^2$$

2.4.

2.4.a

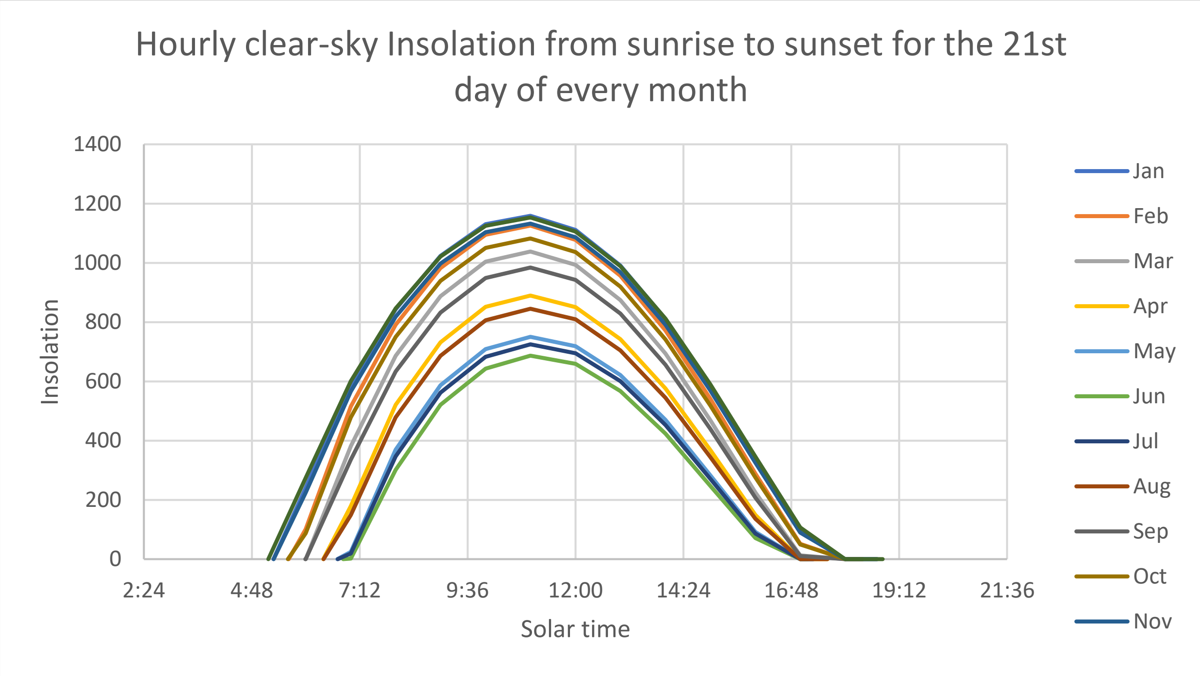


Figure 5 - Hourly clear-sky Insolation from sunrise to sunset for the 21st day of every month

[The full table and calculations used to acquire these results can be found in *Sheet 2* of the assignments accompanying excel file.]

2.4.b

For section 2.1.d we know that the obstruction casts a shadow between 9 to 10amin May, 7:30 to 9am in June and 8:30 to 9:30am in August. Using our tables in *Sheet 2* of the excel file, we can calculate how approximately how much insolation is lost on the 21st day of each month:

$$Insolation\ lost\ on\ the\ 21st\ of\ May = insolation\ between\ 9\ and\ 10am$$
$$= \mathbf{586.5752}\ W/m^2$$

$$Insolation\ lost\ on\ the\ 21st\ of\ June = insolation\ between\ 7{:}30\ and\ \ 9am$$
$$= \frac{1}{2}(1.4548) + 301.534$$
$$= \mathbf{302.26}\ W\ /m^2$$

$$Insolation\ lost\ on\ the\ 21st\ of\ August = insolation\ between\ 8{:}30\ and\ \ 9{:}30am$$
$$= \frac{1}{2}(479.12) + \frac{1}{2}(686.47)$$
$$= \mathbf{582.795}\ W\ /m^2$$

2.4.c

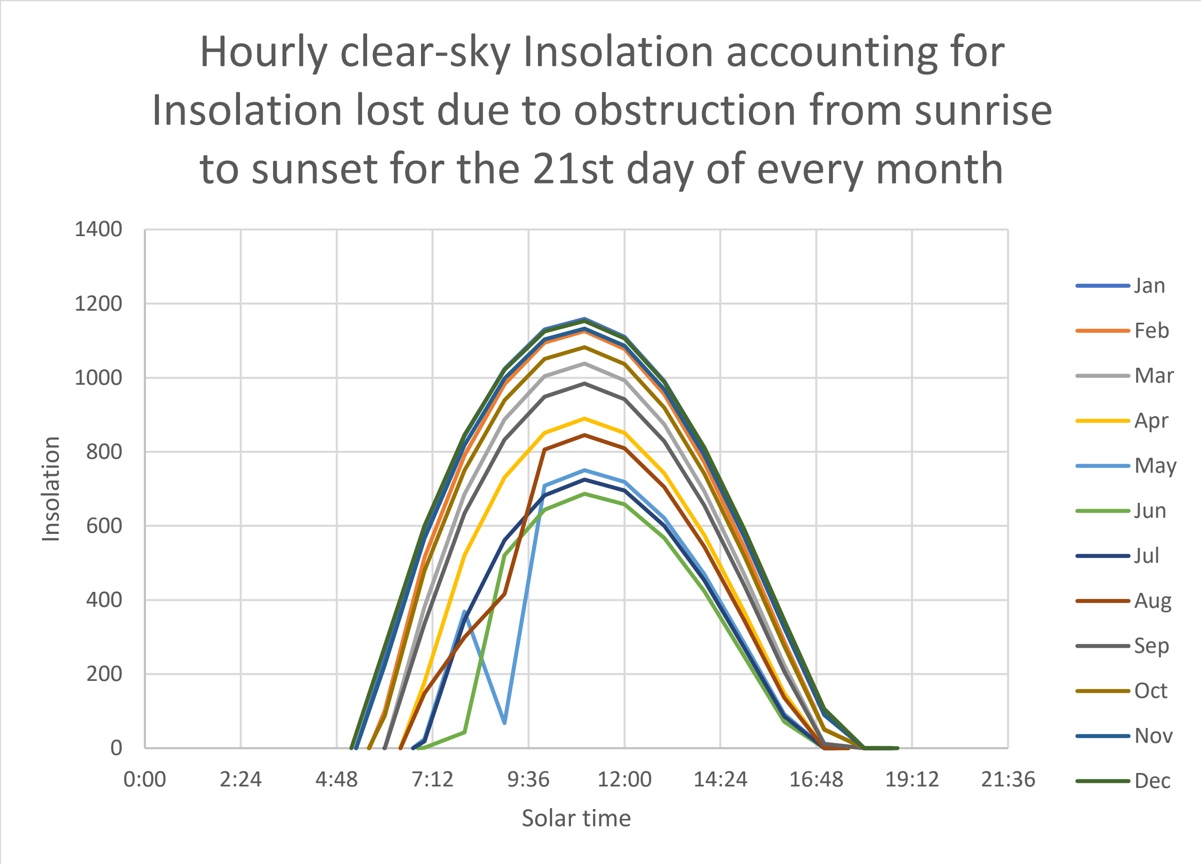


Figure 6 - Hourly clear-sky Insolation accounting for Insolation lost due to obstruction from sunrise to sunset for the 21st day of every month

[The full table and calculations used to acquire these results can be found in *Sheet 2* of the assignments accompanying excel file.]

Assuming the insolation on the 21st day of every month approximates the average insolation from every day of that month, we can find the net annual insolation by multiplying the number of days in a given month with the total insolation acquired on the 21st of that month. The total insolation is summed in *Sheet 2* of the excel file. Therefore:

$$\begin{aligned}Net\ annual\ insolation &= 31*8905.691+28*8297.237+31*7263.563+30*5856.539+31\\&*4105.406+30*3863.151+31*4439.727+31*5055.032+30*6818.236\\&+31*7928.715+30*8672.964+31*8969.242\\&= \mathbf{2\,435\,337.992}\ W/m^2\end{aligned}$$

2.5.

2.5.a

Given number of panels is 34 and number of cells on the panels is 60 (with dimensions 156x156mm), we have the area of the array that absorbs insolation is 49.64 m^2 .

$$\begin{aligned}Annual\ electrical\ energy &= 90\%*15\%*\ 95\%*net\ annual\ insolation*49.64m^2\\&= 0.9*0.15*0.95*2435337.992*49.64\\&= \mathbf{15\,504.17}\ kWh\end{aligned}$$

2.5.b

Assuming GST is 10%:

$$Capitol\ cost = 34\ modules + 3\ inverters + 3\ mounting\ kits + 3\ instalation\ package$$
$$= \big(34 * 225 + 3(950 + 750 + 1650)\big)(1.1)$$
$$= \$19470$$

$$Initial\ Cost = Capitol\ Cost - 3 * Gov.rebate$$
$$= 19470 - 3 * 2331$$
$$= \$12477$$

$$Maintenance\ cost = 0.05 * 19470$$
$$= \$973.5 per\ year$$

$$Money\ back\ from\ grid = 0.03 * 0.4 * 15504.17$$
$$= \$186.05 per\ year$$

$$Money\ saved\ not\ paying\ power\ bill = 0.2933 * 0.6 * 15504.17$$
$$= \$2\,728.42 per\ year$$

$$Net\ yearly\ return = 186.05 + 2\,728.42 - 973.5$$
$$= \$1940.97$$

$$Years\ to\ payback = \frac{12477}{1940}$$
$$= 6.43 \sim \mathbf{7\ years}$$

2.5.c

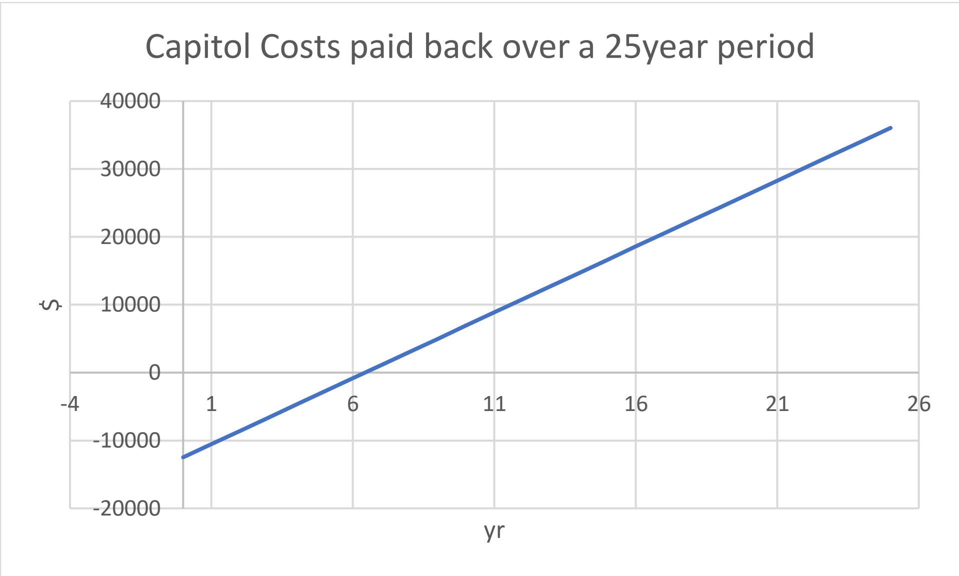


Figure 7 - Capitol Costs paid back over a 25year period

[The full table and calculations used to acquire these results can be found in *Sheet 3* of the assignments accompanying excel file.]

2.5.d

[ran out of time]

3. Conclusion

In conclusion, the calculations and graphs produced in this report show the most effective location for a given PV array on a shed near Meekatharra, what effect an obstruction has on a said PV array and the finances associated with the PV array. This report is meant to be read alongside the assignment brief (see section 5 Appendix 1: Assignment Brief). and it can be seen all tasks (apart form Q5(d)) were completed.

4. References

"Crystalline Silicon PV Modules Installation Manual (IEC Version)." n.d. Accessed April 14, 2022. https://saegroup.com.au/wp-content/uploads/2019/08/Luxen-Solar-Panel-Installation-Guide.pdf.

"Solar Panel Orientation - Energy Education." n.d. Energyeducation.ca. https://energyeducation.ca/encyclopedia/Solar_panel_orientation#:~:text=In%20the%20northern%20hemisphere%2C%20the.

5. Appendices

Appendix 1: Assignment Brief

ELEN3004/ELEN6013 RENEWABLE ENERGY PRINCIPLES

Semester 1 - 2022

Assignment

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

Instructions:

Due Date and Time: **Thursday 14th April 2022, 5PM AWST (Perth Time)**.

Type of Assessment: The assignment report is an individual assessment.

Submission:

1. Submit the following files to the Blackboard submission link for the Assignment in the 'Assessments' folder of Blackboard unit site. (i) A pdf file **not more than 11 pages** answering all parts of the problem given here (including the cover page and references), (ii) The computer program that generated results of the report and (iii) The Turnitin similarity report/s of both the pdf file.

   Pages beyond 11 in the pdf file will not be marked.
2. You may submit any time before the due date and time once the submission links are open. Marks are deducted for late submissions as given in the unit outline.
3. Any applications for assessment extensions should be submitted via Curtin Connect online system with valid documentary proof of the cause.

Academic Integrity:

Sharing solutions is completely unacceptable among students and is deemed as plagiarism. Any similarities found in reports and computer programs with those of other groups or any other sources will be investigated. Any similarity with this assignment problem will be ignored. Any case of plagiarism will be reported to the university and handled according to the university academic integrity policy. As this is an assessment of the unit, requests for individual or group consultations on the assignment will not be accepted, to be fair with all students.

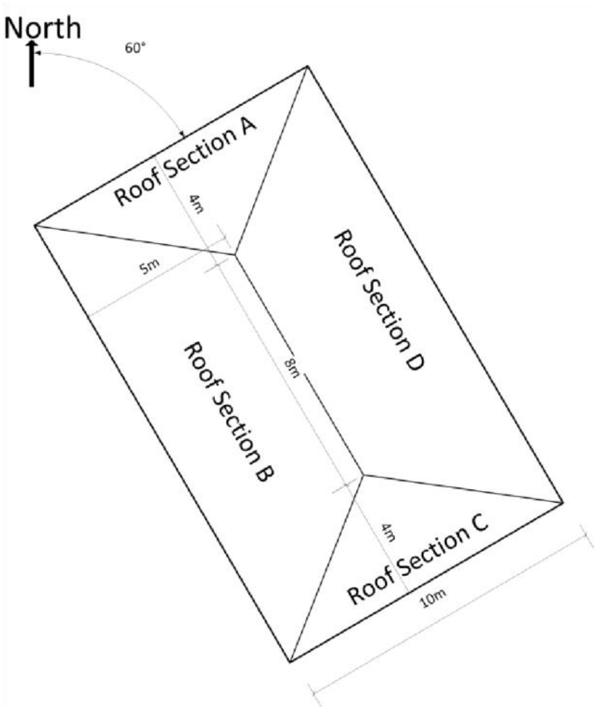
Format of the Report:

1. The cover page of the report should clearly show the title of the assignment, unit code, unit name, semester, year, names of student and student ID number.
2. Answer the questions in the given order.

3. For each part: (a) show the problem number, (b) **present the equations** used, (c) give the **numerical calculation** or a **sample calculation** for a meaningful condition (Ex. during daytime) for repetitive calculations, (d) present the **graphs, tables** and any other important steps of calculations leading to the **final results**.
4. Clearly **highlight** your final answers. Presentation aspects such as cover page content, captions and neatness of figures, tables, numbering of parts sequentially, highlighting any numerical results, clear language, showing references and keeping the report to the page limit will be assessed.
5. Do not attach unnecessary tables of data generated by computer programs. Only present those requested in the problem.
6. A copy of lines from a computer program is **not accepted** as a sample calculation and will not be given marks. You need to show the working in an understandable manner.
7. The report is expected to be typewritten using a computer.

Assignment Problem:

You are required to design a 3 kW STC rated grid-connected photo-voltaic (PV) array as a roof-top installation for a shed near Meekatharra whose latitude is 26.5° South. The plan view of the roof is as shown in Fig. 1. The tilt angle of the roof is 22°.



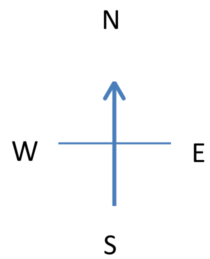


Fig. 1 Plan view of the roof

Viewing from the site towards North, following obstruction could be sighted.

Building : azimuth angle range from 45° to 60° to East; altitude angle at the top=45° The 250 W PV module available is 'Hareon Solar HR-250P-18/Bb - Poly-Crystalline Silicon Module' whose specifications sheet is available at https://www.sicleanenergy.com.au/wpcontent/uploads/2014/06/3BBHR-230P-18-Bb-HR-250P-18-Bb.pdf . However, there should not be any overhanging parts of modules that go beyond the area of a selected section of the roof. Also all modules should be limited to one section of the roof. Splitting the array on to more than one roof section is not acceptable. Your report should consist of the following parts.

1. (a) Show the sample calculations for the sun's position angles at 6am on 1st January at the site. What is the period of daylight on this day?

   [5 Marks]

   (b) Give the sunrise and sunset times on the 21st of each month of the year in a table.

   [5 Marks]

   (c) Draw the sun-path diagram by calculating the sun's position angles hour by hour from sunrise to sunset on 21st day of each month of a year.

   [10 Marks]

   (c) On the same diagram draw the obstruction that could shadow the site. You may assume rectangular shape for the obstruction. Give the hours of shadowing by obstruction in different months of the year. Estimated answers using the graph is acceptable with a maximum error of 30 minutes.

   [5 Marks]

2. (a) What is the maximum number of solar PV modules that can be installed on each section of the roof without causing any overhanging parts? You may use mathematical, graphical or other means for the answer here. How many PV modules are required to be installed?

   [5 Marks]

   (b) Based on the orientation of the roof sections, give the order of roof sections receiving the highest annual insolation to lowest annual insolation per square metre. You should not make any insolation calculations here but logically justify your answer very briefly.

   [5 Marks]

   (c) Based on the answers to parts 2(a) and 2(b), select the best suitable section of the roof for the installation of PV array.

   [5 Marks]

3. (a) Show the sample calculations for the total insolation on a collector on the selected roof section at 10am on January 1st. You may assume the reflected component of insolation to be zero and the sky diffuse factor (C) to be 0.1.

   [5 Marks]

4. (b) Plot the hour by hour clear-sky insolation from sunrise to sunset on the selected section of roof for 21st day of each month of a year. You may assume the reflected component of insolation to be zero and the sky diffuse factor (C) to be 0.1.

   [10 Marks]

   (c) How much insolation is lost in each month due to the obstruction? You may assume the beam insolation on the collectors to be zero when the site is shadowed by the obstructions.

You may assume the reflected component of insolation to be zero and the sky diffuse factor (C) to be 0.1.

[10 Marks]

(d) Plot the variation of net insolation on 21st of each month to calculate the net annual insolation.

[10 Marks]

5. (a) Assuming 10% of net insolation in a year is lost due to cloudy and rainy periods, the practical annual average conversion efficiency of solar PV modules to be 15% and that of the MPPT inverter to be 95% calculate the annual electrical energy produced by the entire PV array in kWh.

[5 Marks]

(b) The utility pays $0.03 per kWh supplied to the grid. The tariff for the electricity purchased from the utility company is $0.2933/kWh. The costs and rebates of system components are as given in Table 1. Assume 60% of the energy produced by the array will be consumed by the owner. Assume the government rebate is available at the installation time. Calculate the simple payback period for the installation by assuming 5% of capital cost as the maintenance cost.

[10Marks]

(c) Plot how the capital costs are paid back over a period of 25 years. What is the profit/loss after 25 years?

[5 Marks]

(d) How much loss of income was caused by the obstruction over 25 year period?

[5 Marks]

Table 1

Item	No.	Price
Hareon Solar HR-250P-18/Bb - Poly-Crystalline Silicon Module’	1	$225+GST
Rewatt 3000TL Inverter	1	$950+GST
Mounting Frames (middle clamp, End clamp, rails, Earthing lugs)	3 kW kit	$750 +GST
Installation charge of a 3 kW system (no-split, single storey, one inverter)	1	$1650 +GST
Government Rebate for 63 Renewable Energy Certificates (REC) generated by 3kW system		63x$37 = $2,331

END OF ASSIGNMENT PROBLEM.