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**MODULE TITLE: Solar Energy: Technology, Modelling and Analysis**

**MODULE NUMBER: MEC11121** ______________________________

**NAME OF MODULE LEADER: Professor Tariq Muneer**

**(Dr.Keng Goh for this coursework)**

**DATE OF SUBMISSION: 7 December 2018** _____________________

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Edinburgh Napier University

# Analysis of solar geometry and irradiation

Coursework 2

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12-7-2018

## Abstract

The purpose of this report is to critically evaluate the solar geometry and analyse the global horizontal irradiation (GHI) for the roof top of University of Edinburgh's library with the given data in January and June, through MATLAB software. Further, assessing the energy output from PV system.

In January, the irradiation data was missing for 16 days, only 15 days of data was taken into account for analysis. And there was lost data from 7:25 to 10:50 on 18$^{th}$. Moreover, some data contained negative value. The data was treated by replacing zero to the cell. In June, the data was disappeared on 10$^{th}$ and 18$^{th}$ for 8 hours. The data treatment was done the same way as in January.

The method for evaluating solar geometry was done by plotting solar altitude and solar azimuth on solstice at January, 22 and June, 22. Additionally, the shadow profile was observed through Google Earth Pro (2018) to evaluate the location. Secondly, the hourly mean GHI and DHI was calculated and plotted to analyse the irradiation for each month. Both analysis was done by MATLAB and excel sheet from Muneer. All MATLAB codes developed for the analysis are in Appendix.

As a result, the chosen location is generally good for PV installation as there is no shadow during the day and no obstruction at the south direction where the highest energy output occurred. The PV structure is designed to at optimum tilt angle 35°. However, due to the space on the roof, it is better to put the panels toward south-east at 168° and the energy output only decreased 2%. From the different between GHI and DHI irradiation plotted, the PV tended to receive more sun ray in June, while in January, most power source was from diffuse irradiation or from sky.

Further, the return of investment should be done in order to determine whether the project is feasible or not because the energy generated from PV system is cover only 6% and even less than 1% in June and January respectively.

## Contents

**List of figures**



**List of tables**

# 1 Introduction

Practically, before starting any construction project, the feasibility study should be done in order to assess whether the project is worth to invest or not or to foresee the possible obstacles. Similar to PV project, the site evaluation and irradiation analysis helps gaging the energy output and possibility of the project before the investment.

As energy output from PV is dependent on the sun and daylight, it is critical to identify the sun position on the installation site and the obstructions that might create shadow on PV. Moreover, solar geometry analysis can help finding the optimum direction of PV that be able to capture the sun ray throughout the day.

In order to assess the energy output from PV, the global horizontal irradiation data should be analysed as well, because it is the main source for generating power. Together with solar geometry analysis, the optimum tilt angle of PV can be determined to reach the highest efficiency of PV. In this report, MATLAB was deployed to assist both analysis.

# 2 Data source

The data used to analyse is solar data in Edinburgh, UK (Lat. 55.95, Long. 3.20) for January and June in 1993. The data contains following information shown in table 1. The information employed in the analysis was diffuse and global horizontal irradiation, solar altitude and solar azimuth. All data was recorded every 5 minutes, throughout the sunshine duration.

*Table 1 Information in data source*

| Column | Symbol | Description |
|---|---|---|
| 1 | | Month |
| 2 | | Day |
| 3 | | Year |
| 4 | | Hour |
| 5 | | Minute |
| 6 | $E_{vg}$ | Global Horizontal Illuminance, lux |
| 7 | $E_{vd}$ | Diffuse Horizontal Illuminance, lux |
| 8 | $E_{vgn}$ | Vertical Illuminance, North Facing Surface, lux |
| 9 | $E_{vge}$ | Vertical Illuminance, East Facing Surface, lux |
| 10 | $E_{vgs}$ | Vertical Illuminance, South Facing Surface, lux |
| 11 | $E_{vgw}$ | Vertical Illuminance, West Facing Surface, lux |
| 12 | $E_{eg}$ | Global Horizontal Irradiance, |
| 13 | $E_{ed}$ | Diffuse Horizontal Irradiance, |
| 14 | $E_{egn}$ | Vertical Irradiance, North Facing Surface, |
| 15 | $E_{ege}$ | Vertical Irradiance, East Facing Surface, |
| 16 | $E_{egs}$ | Vertical Irradiance, South Facing Surface, |
| 17 | $E_{egw}$ | Vertical Irradiance, West Facing Surface, |
| 18 | $SOLALT$ | Solar Altitude, degrees |
| 19 | $SOLAZM$ | Solar Azimuth, degrees clockwise from due North |
| 20 | $C_{ef}$ | Shade ring correction factor for horizontal diffuse irradiance, dimensionless |
| | $C_{vf}$ | Shade ring correction factor for horizontal diffuse illuminance, dimensionless |

The data in January generally started recording from 7:25 to 16:55, whilst, the data in June began from 3:35 to 21:55. After preliminary checked, some data were missing and some of irradiation data were negative value. The proper investigation of missing and strange data was further explained for each analysis in section 3.

# 3 Solar Data Analysis

## 3.1 Solar geometry evaluation for Edinburgh

### 3.1.1 Solar geometry

The position of the sun can be located by two parameters, solar altitude (SOLALT) and solar azimuth (SOLAZM). *Solar altitude* is the elevation angle of sun above the horizon. The value of SOLALT ranges from 0° to 180°. *Solar azimuth* is the angle in horizontal plane from north of sun beam, starting from 0° clockwise. These co-ordinates are varied by the location. (Muneer, et al., 2004)

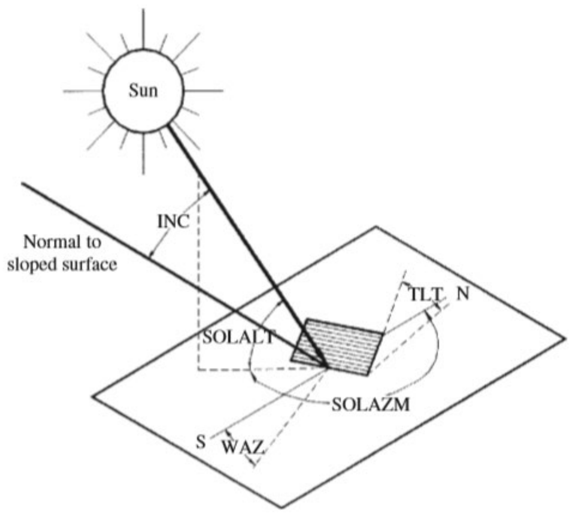


*Figure 1 Solar geometry of a sloped surface (Muneer, et al., 2004)*

And because the solar geometry is different for specific location, it is essential to know the solar geometry at the PV installation site to determine the optimum tilt angle and the direction of the panel.

### 3.1.2 Location solar PV installation site

The chosen location for analysis is the roof of university of Edinburgh's library as shown in Fig.2. The solar panels were assumed to face south-east direction at SOLAZM, 168°. The height of the building is 102 m. The installation area is approximately, 2,130 $m^2$. (Google Earth Pro, 2018).

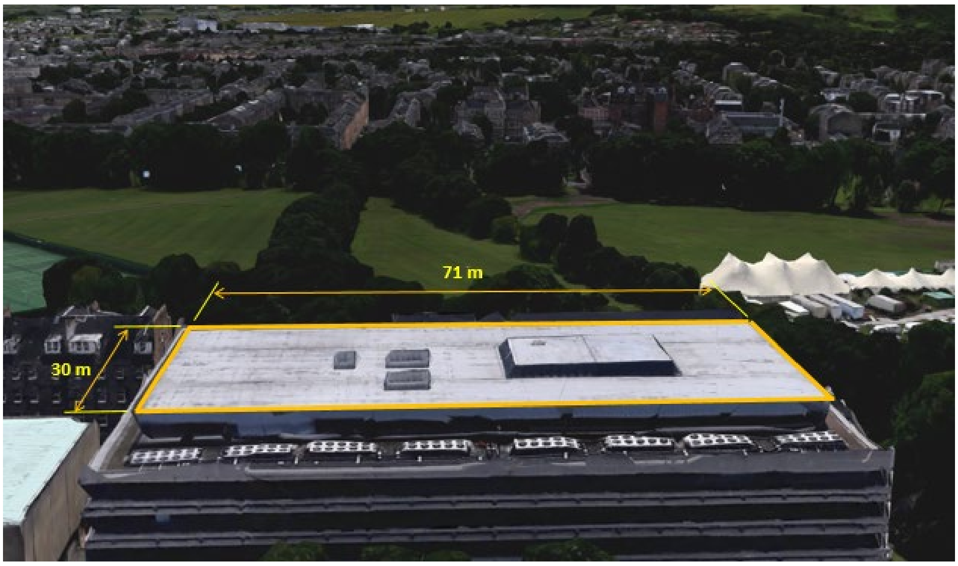


*Figure 2 the roof of university of Edinburgh's library (Google Earth Pro, 2018)*

### 3.1.3 Analysis Method

The steps for doing solar geometry analysis are described in the Fig.3. The first two steps were done in section 2.

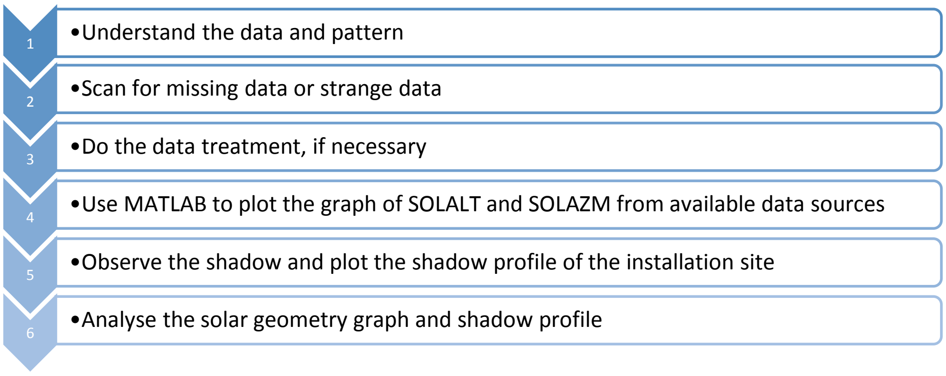


*Figure 3 data analysis method for solar geometry*

#### *Solar geometry analysis*

The SOLALT and SOLAZM on the solstice - January, 22 and June, 22 were used to plot the solar geometry in this report. The negative SOLALT were discharged from the graph as the sun position was below the horizon.

The SOLALT and SOLAZM data for January, 22 and June, 22 are consistently recorded and no missing data or strange number. The yellow highlight in fig.4 represented the data that are less than zero. These negative values were not considered in plotting graph.

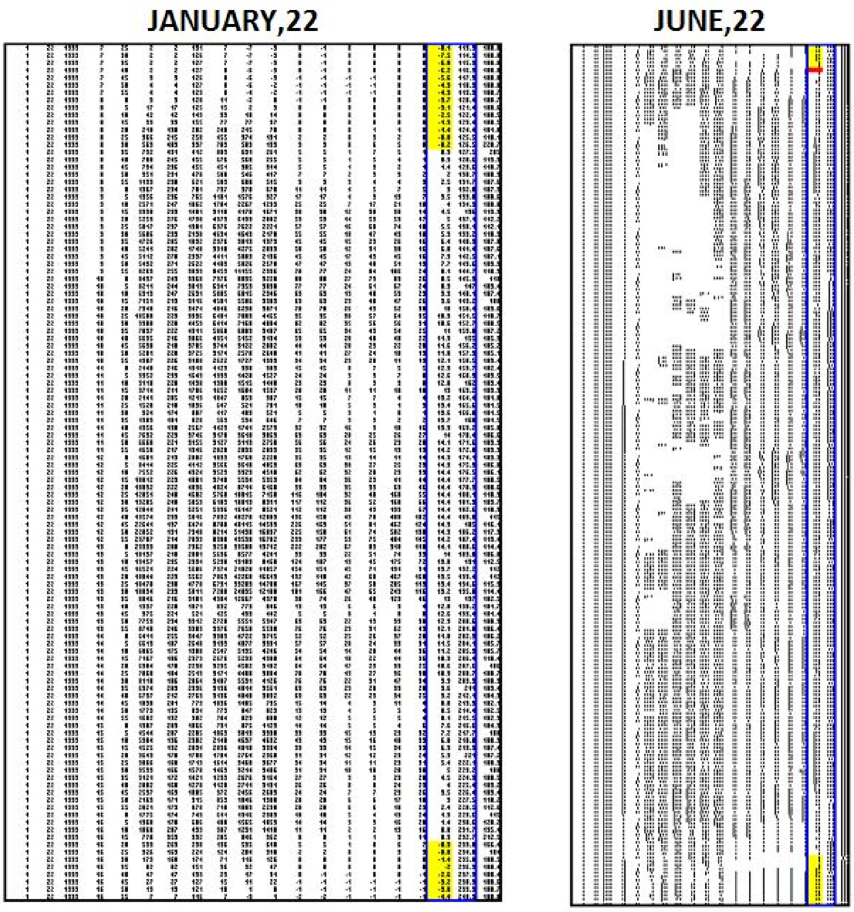


*Figure 4 raw data of SOLALT and SOLAZM of January, 22 and June, 22*

MATLAB was employed to plot the solar geometry graph as shown in fig.5. The MATLAB code for plotting the solar geometry graph is demonstrated in Appendix A.1.

### *Shadow profile analysis*

To maximize the power output, shading should be avoided on the solar panel. The shadow profile can be simply observed on the site or using software to forecast (e.g. Autodesk Ecotect Analysis). In this report, Google Earth Pro (2018) was used to get the landscape, elevation, azimuth and distance at the chosen site. As shown in fig.4, anything above the horizon potentially creats the shadow. In order to plot the shadow profile, two variables must be known; azimuth and elevation angle, looking from the installation site to obstacles. The elevation angle can be obtained from Trigonometry $\theta = \sin^{-1}(\frac{elevation,m}{distance,m})$.

Five points of obstacles were pinned to create shadow profile as presented in table 2 and plotted the shadow profile by SunEarthTools.com (2018).

*Table 2 detailed of obstacle point (Google Earth Pro, 2018)*

| | distance,m | elevation,m | AZM | sinϴ | ϴ |
|---|---|---|---|---|---|
| **Point1** | 5987.26 | 146 | 151.43 | 0.0073 | 0.4211 |
| **Point2** | 6412.15 | 150 | 159.8 | 0.0075 | 0.4289 |
| **Point3** | 7425.71 | 171 | 176.16 | 0.0093 | 0.5324 |
| **Point4** | 6651 | 351 | 190.34 | 0.0374 | 2.1450 |
| **Point5** | 7262 | 470 | 205.01 | 0.0507 | 2.9034 |

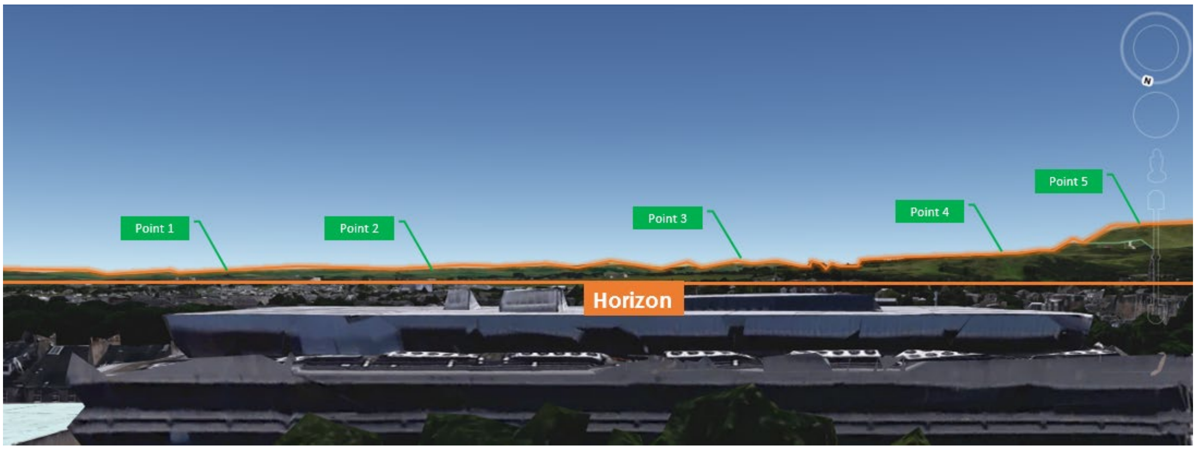


*Figure 5 Landscape at the chosen site (Google Earth Pro, 2018)*

### 3.1.4 Analysis result

Solar geometry graph plotted from MATLAB is shown in Fig.6. From the graph, the highest elevation angle in January is much less than in June. This means in January, the daylight period is shorter than in June because the lesser distance of sun path. As the energy output of PV depends on the daylight period, consequently, the PV is expected to generate smaller amount of energy output in January than in June.

In addition, the elevation angle of the sun also has a vital role in determining the optimum tilt angle of panel as the highest energy output happens when the sun beam is perpendicular to the panel plane. So the optimum tilt angle in January is different from June. Generally, the best practice is to adjust the tilt angle for each month to capture the most sun ray.

Another factor that affects the PV system is panel direction. As shown in the solar geometry graph (fig.6), putting the panel toward south would allow the panel to expose to the sun ray from east to west. In contrast, the panel has lower chance to receive the sun beam directly if the direction of panel is set toward north or west.

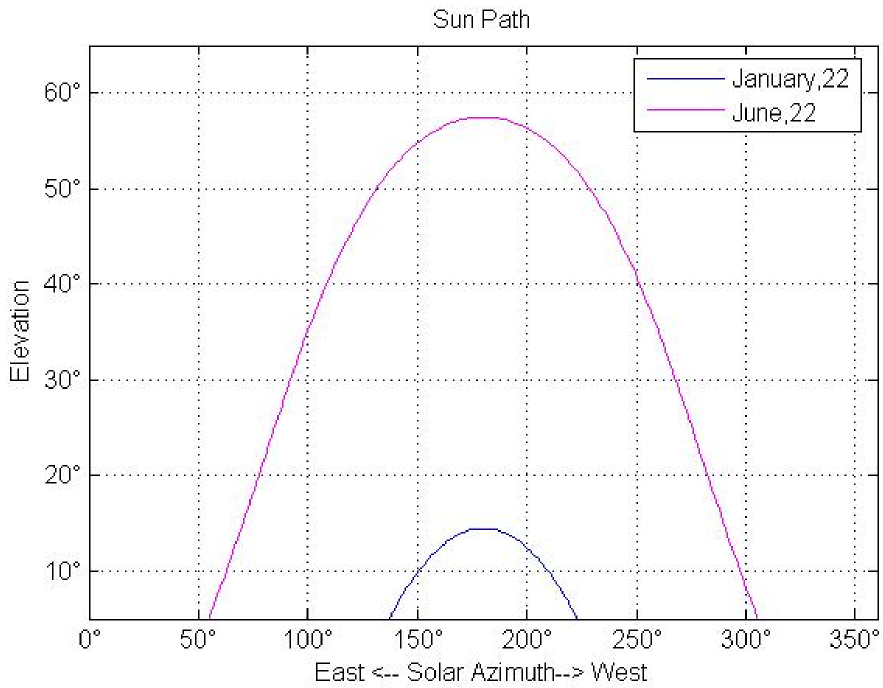


*Figure 6 Solar geometry of January and June on solstice (see MATLAB code in Appendix A.1)*

In opposition to the sun ray, the shadow should be avoided when designing PV system. Fig 7, is the shadow profile plotted from SunEarthTools.com (2018) for the chosen location. From the graph, the shadow has negligible effect on power generation from PV, both in January and in June because the shadow occurs when the sun almost goes down. Though, the panel still get the sun ray throughout the day.

As a result from the analysis, the best direction of panel should be fixed toward the south.

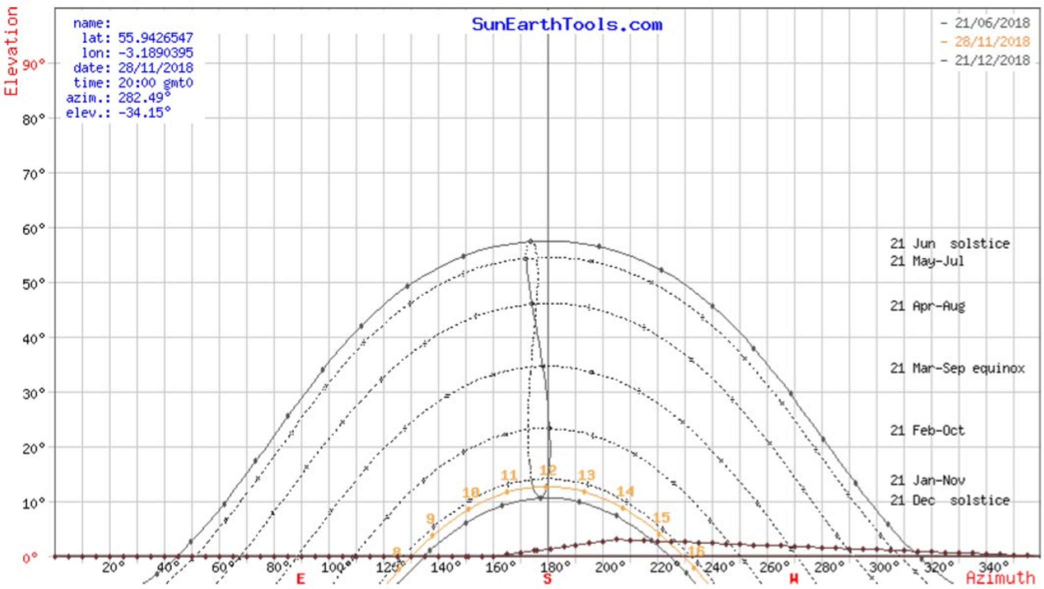


*Figure 7 Solar geometry and shadow profile plotted from SunEarthTools.com (2018)*

## 3.2 Solar irradiation analysis

Radiation from the sun is the main source of power for PV. Therefore, it is crucial to analysis solar irradiation data prior to assess the energy generation from PV system. There are two forms of irradiation data given, global and diffuse horizontal irradiation. Global horizontal irradiation (GHI) is radiation from sun light measuring at horizontal surface, whereas, the diffuse horizontal irradiation (DHI) is radiation from the sky.

### 3.2.1 Analysis method

The analysis process is described in the diagram (Fig.8) below.

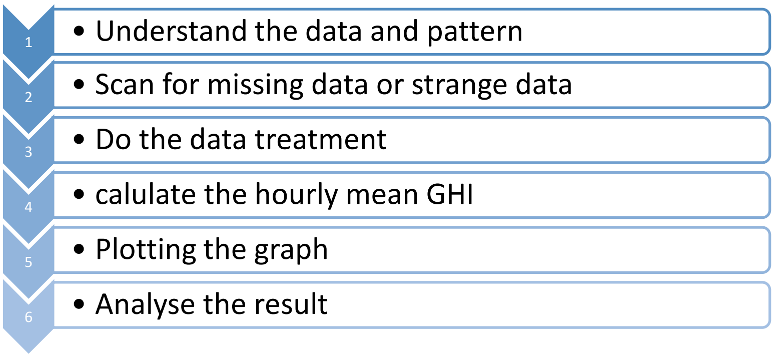


*Figure 8 data analysis diagram for GHI analysis*

#### 3.2.1.1 Data treatment

The irradiation data was rearranged by MATLAB to facilitate data checking. Each column contained the data for each day and time (every 5 minutes) for each row, as shown in Fig 9. The MATLAB code for rearranging the data can be seen in Appendix A.2.

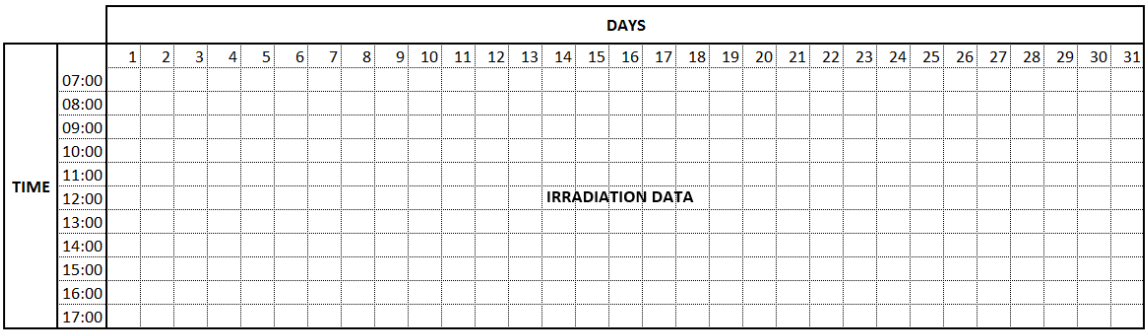


*Figure 9 The structure of rearrange data*

Basically, the code checked if there is data in each day and each time slot. If there is no data, the cell is to be replaced with zero. The result of rearranged data is illustrated in Fig.10 and Fig., for January and June respectively.

### January

As shown in Fig.10, there were 16 days that the data was missing. Therefore, the analysis only took the data available in 15 days into account.

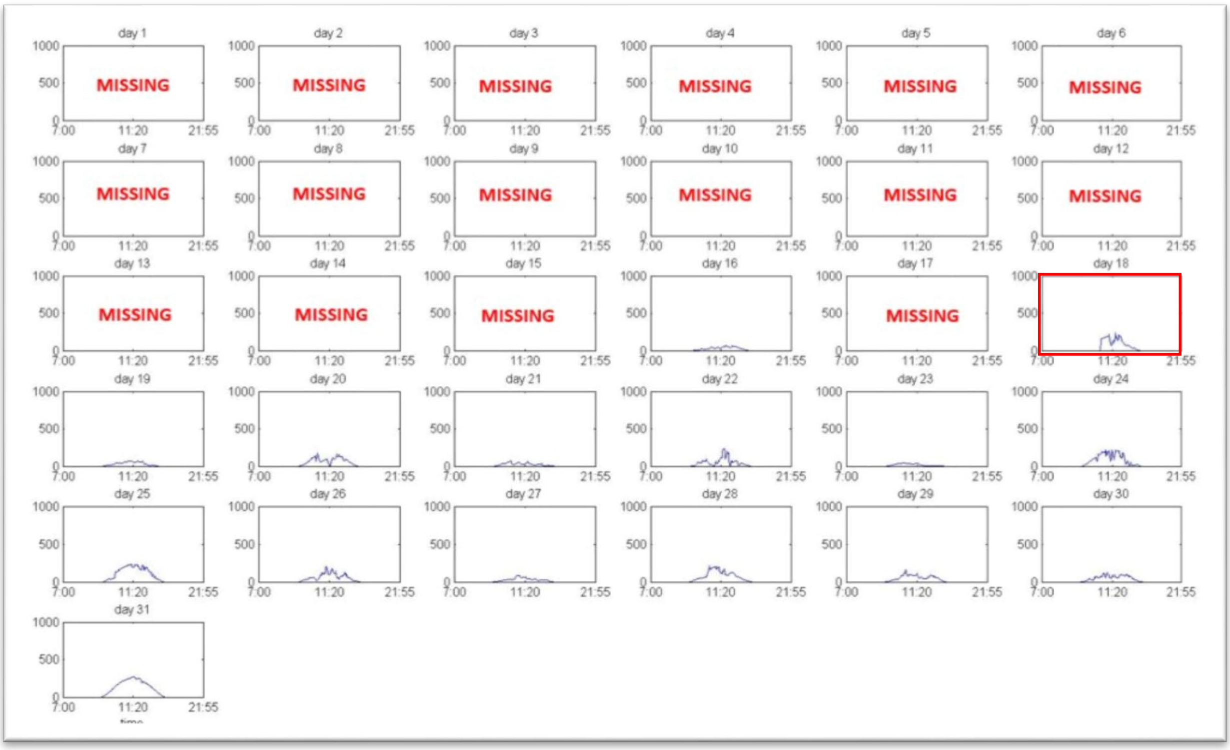


*Figure 10 Daily GHI graph in January (see MATLAB code in Appendix A.3)*

In January, the data was recorded from 7:25 to 16:55, every 5 minutes. From the graph in Fig.10, the chunk of data in day 18 is missing from 7:25 to 10:50. Though, nearly 50% of the data is missing on this day, the rest is still useful to analyse the hourly GHI.

### June

The data in June is generally good, except on day 10 and 18. The data was recorded from 3:05 to 21:55 for each day. But in day 10 and 18, the data is missing more than half day from 6:00 to 14:55 and from 13:50 to 21:55, respectively. With the same principal applied for data in January. These two days were considered in hourly GHI.

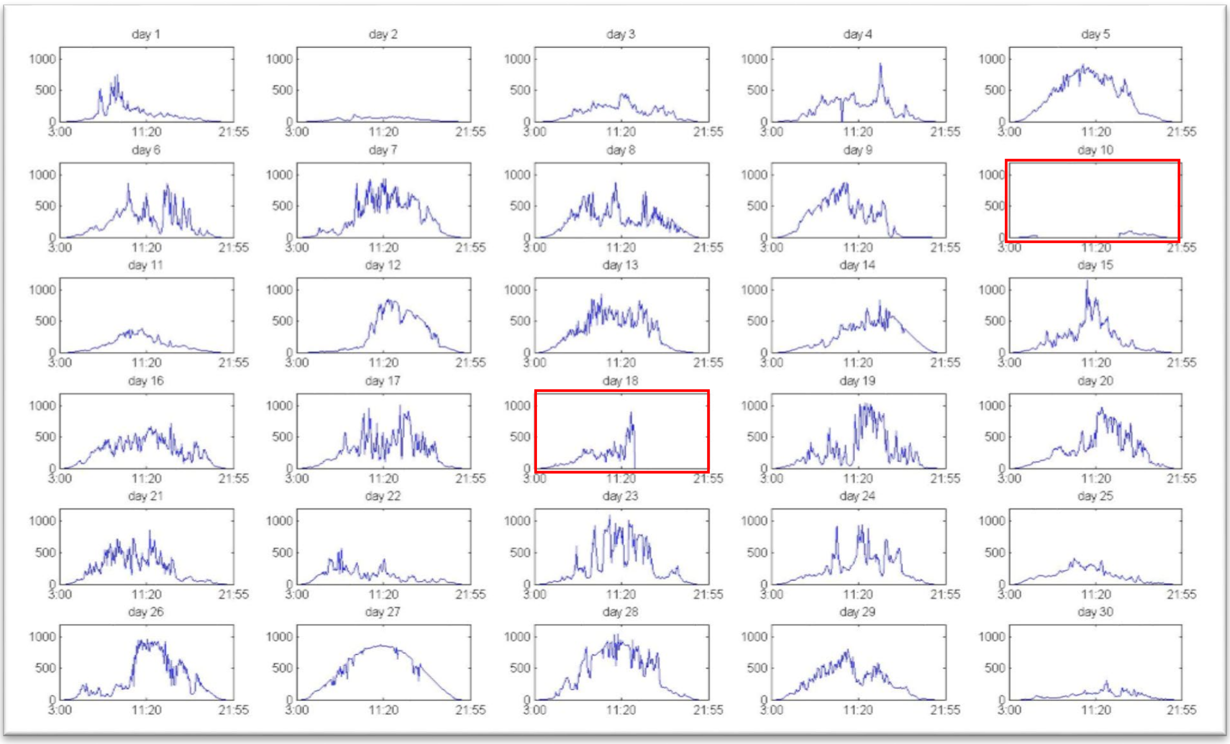


*Figure 11Daily GHI graph in June ( see MATLAB code in Appendix A.3)*

#### 3.2.1.2 Hourly global horizontal irradiation

After did the data treatment in previous step, the hourly values in each day are lined up in a row. Thus, the mean hourly values can be obtained by sum all values in each row and divided by number of days. But the missing data in time slots mentioned in data treatment step earlier were not considered when calculating the mean in those slots. However, the rest of the data on those days were still used.

*Table 3 Summary of missing data*

| Date | Time slots that the data is missing | % of missing data to all data |
|---|---|---|
| **18-January** | 7:25 – 10:50 | 3.3% |
| **10-June** | 6:00 – 14:55 | 1.5% |
| **18-June** | 13:50 – 21:55 | 1.3% |

MATLAB was deployed to plot the irradiation graph for both, January and June. MATLAB code is demonstrated in Appendix A.4.

### 3.2.2 Analysis result

The different between GHI and DHI represents the magnitude of sun beam. In January, the different between these two irradiation was not much different during the morning and evening. It means there was small amount of sun ray, the majority of power source was from the sky.

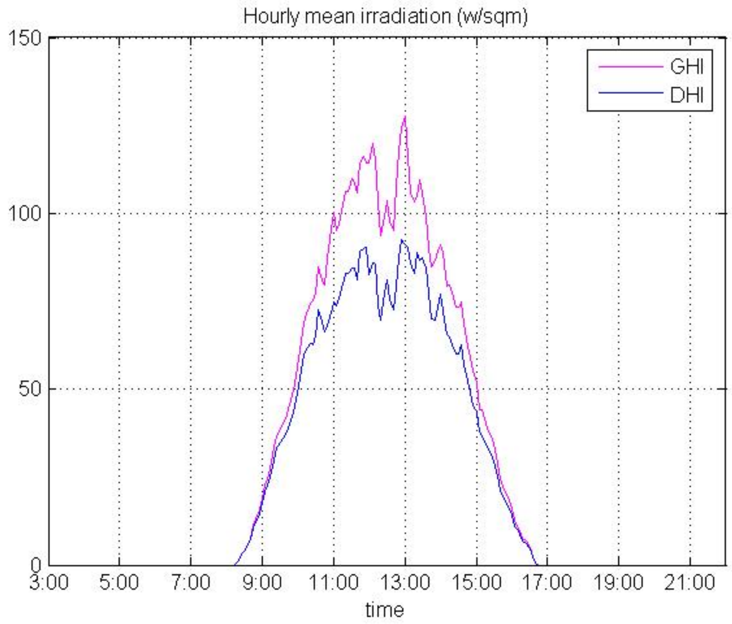


*Figure 12 Hourly mean GHI and DHI in January (see MATLAB code in Appendix A.4)*

In contrast, the different between GHI and DHI in June was considerably large. In another word, the sunshine averagely started since morning and much more during noon time, and gradually decrease in the evening.

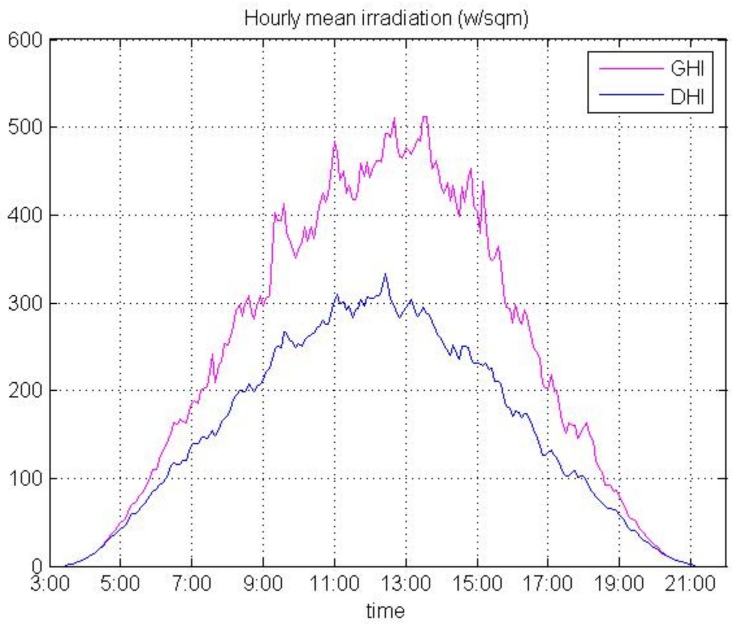


*Figure 13 Hourly mean GHI and DHI in June (see MATLAB code in Appendix A.4)*

Therefore, in January, the tilt angle and elevation angle of the sun did not significantly have effect on power output, because mainly the irradiation came from sky. While in June, the elevation angle of the sun played vital role in generating energy output. Hence, the optimum tilt angle between these two months is 35°.

# 4 Energy output from solar

Commercial solar panel used to estimate the energy output is from Canadian solar. The specification is summarized in Appendix B. With consideration on row space between modules, the total installable panels are 315 panels.

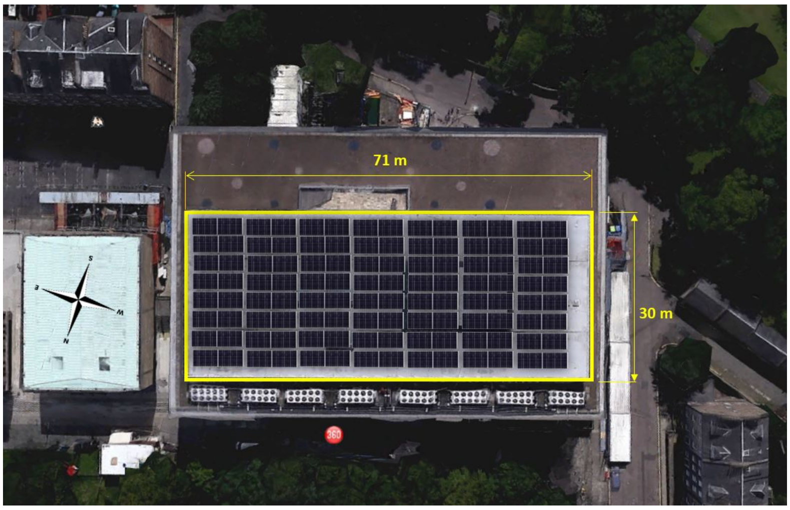


*Figure 14 PV installation site ( Picture from Google Earth Pro(2018), own modified)*

To calculate the energy output, hourly mean GHI and DHI were used in excel spreadsheet from Muneer for both January and June. MATLAB code to extract GHI and DHI is shown in Appendix A.5. The panels' direction is set toward south-east, 168°. The result is illustrated in the graph below (fig.). Approximately, in June, the total energy output is 16.41 MW and 2.53 MW in January. With the given irradiation data, the energy generated in June is higher than in January around 6 times.

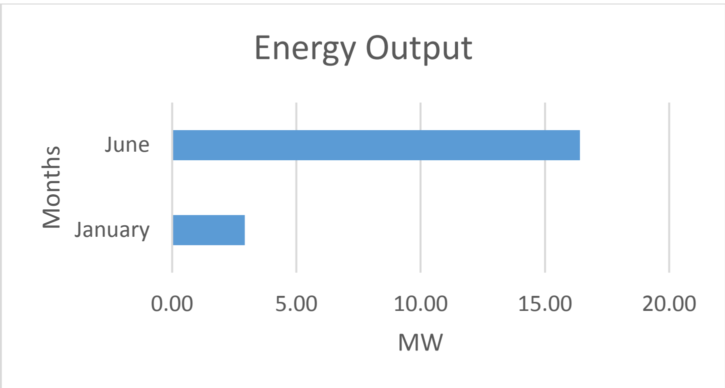


*Figure 15 Estimated energy output in January and June*

# 5 Conclusions

## Location

From solar geometry and shadow profile analysis, the rooftop of University of Edinburgh is suitable for installing PV. As there is no major obstruction at the south where it allows the panel to capture the sun ray from east to west. The shadow from mountain is also negligible as it is likely to happen when the sun almost goes down where the irradiation is quite low. But for the space wise, the panels are better set toward south-east at the azimuth of 168°. The energy output is estimated to be decreased around 2% from putting the panel to the south.

## Global horizontal Irradiation

For the analysis of GHI, the mean hourly GHI in June is much higher than in June, as a result of daylight period and elevation angle of the sun. Further the analysis indicated that the peak of GHI occurs on the mid of the day where solar azimuth is 180° at elevation angle, 15° and 55° for January and June, correspondingly. Thus, tilt angle of panel is designed at 35°.

## Energy output

Though energy output in June is greater than in January, both are not be able to cover the energy consumption monthly. The energy saved by deploying PV system is 6% and less than 1% in January and June, respectively. The monthly energy consumption for the library was estimated from the equation below.

$$Monthly\ energy\ consumption = \frac{Annual\ energy\ consumption\ per\ m^2 \times library\ area}{12}$$

The annual energy consumption for typical building is $120\ kWh/m^2$ (European commission, 2005). The usable area in University of Edinburgh's library is $27{,}961\ m^2$ (RIAS, 2013). Therefore, the monthly energy consumption is $279.61\ MW$.

Hence, the further assessment on the return of investment should be done, to determine whether this project is feasible or not.

# Appendix A: MATLAB codes

## A.1 plotting solar geometry graph

```
%-----------------------------------------------------------------------------
%                               Solargeometry
%-----------------------------------------------------------------------------
figure(6);plot(S.SOLAZM1(:,22),S.SOLALT1(:,22));
ylim([5 65]);xlim([0 360]);title('Sun Path');xlabel('East <-- Solar Azimuth--> West');
set(gca,'XTickLabel',{'0°';'50°';'100°';'150°';'200°';'250°';'300°';'350°';});
set(gca,'YTickLabel',{'10°';'20°';'30°';'40°';'50°';'60°';'65°';});
hold all;
grid on;
plot(S.SOLAZM6(:,22),S.SOLALT6(:,22),'m-');
legend('January,22','June,22');
```

## A.2 Rearranging irradiation and data treatment

```
%-------------------------------------------------------------------------
%                              Rearrange data
%-------------------------------------------------------------------------
%%Rearrange data, day as column, hour as row,
m=1;%row index for rearrange data
n=1;%column index for rearrange data
p=1;%row index from original data
for a=1:12 %month loop
    check=exist(sprintf('dataset%d',a)');%check if month exist
    if check==1%if it's exist, run the loop
        dataset=load(sprintf('dataset%d.PRN.txt',a));%load data
        for i=1:31%day loop
            check=ismember(i,dataset(:,2));
            for j=3:21 %hour loop
                for k=0:5:55 %minute loop
                    %check if the hour, minutes and the number exist
                    if dataset(p,4)==j & dataset(p,5)==k & check==1
                        GlobalHI(m,n)=dataset(p,12);%assign GHI from the data source
                        DiffuseHI(m,n)=dataset(p,13);%assign DHI from the data source
                        SOLALT(m,n)=dataset(p,18);%assign SOLALT from the data source
                        SOLAZM(m,n)=dataset(p,19);%assign SOLAZM from the data source
                        m=m+1;%move to next row
                        p=p+1;%move to next index
                    else
                        GlobalHI(m,n)=0;%assign 0 the GHI cell
                        DiffuseHI(m,n)=0;%assign 0 the DHI cell
                        SOLALT(m,n)=0;%assign 0 the SOLALT cell
                        SOLAZM(m,n)=0;%assign 0 the SOLAZM cell
                        m=m+1;%move to next row
                    end
                    %if p more than the length of the data, break the loop
                    if p>=length(dataset),break,end
                end
            end
            n=n+1;%move to next column
            m=1;%reset the row to index 1
        end
        n=1;%reset the column
        p=1;%reset the index
        %creat the name to assign to keep in structure data
        ghi=sprintf('GlobalHI%d',a);
        dif=sprintf('DiffuseHI%d',a);
        alt=sprintf('SOLALT%d',a);
        azm=sprintf('SOLAZM%d',a);
        %assign the value to the data in structure
        S.(ghi)=GlobalHI;
        S.(dif)=DiffuseHI;
        S.(alt)=SOLALT;
        S.(azm)=SOLAZM;
        %After assign all values into new file, rewrite the data in next
        %month in the same variable
        GlobalHI=[];
        DiffuseHI=[];
        SOLALT=[];
        SOLAZM=[];
    else,end
end
```

## A.3 plotting daily GHI

```
%-----------------------------------------------------------------------------
%                        Plot graph-daily GHI
%-----------------------------------------------------------------------------
%JAN
j=1;%graph position
for i=1:31%day loop
        figure(1);subplot(6,6,j);
        plot(S.GlobalHI1(:,i));
        ylim([0 1000]);xlim([0 228]);
        title(sprintf('day %d',i));
        set(gca,'XTick',[0,114,228]);
        set(gca,'XTickLabel',{'3:00','11:20','21:55'});
        j=j+1;
end
figure(1);xlabel('time');
% %JUNE
j=1;
for i=1:31
        figure(2);subplot(6,5,j);
        plot(S.GlobalHI6(:,i));
        hold all;
        plot(mean_GHI_jun,'r');
        ylim([0 1200]);xlim([0 228]);
        title(sprintf('day %d',i));
        set(gca,'XTick',[0,114,228]);
        set(gca,'XTickLabel',{'3:00','11:20','21:55'});
        j=j+1;
end
```

## A.4 Calculating the hourly mean GHI, DHI and plotting graph

```
%------------------------------------------------------------------------
%                         Plot hourly mean graph
%------------------------------------------------------------------------
%JANUARY
%calculate the hourly mean GHI
for i=1:length(S.GlobalHI1)
    %calculate the mean only the that is not zero
    mean_GHI_jan(i,1)=mean(S.GlobalHI1(i,find(S.GlobalHI1(i,:))));
    mean_DHI_jan(i,1)=mean(S.DiffuseHI1(i,find(S.DiffuseHI1(i,:))));
end

%JUNE
%calculate the hourly mean GHI
for i=1:length(S.GlobalHI6)
    mean_GHI_jun(i,1)=mean(S.GlobalHI6(i,find(S.GlobalHI6(i,:))));
    mean_DHI_jun(i,1)=mean(S.DiffuseHI6(i,find(S.DiffuseHI6(i,:))));
end
%Plotting the graph, January
figure(3):plot(mean_GHI_jan,'m');xlabel('time');
xlim([0 228]);ylim([0 150]);
set(gca,'XTick',(0:24:216));
set(gca,'XTickLabel',{'3:00','5:00','7:00','9:00','11:00','13:00','15:00','17:00','19:00','21:00'});
title('Hourly mean irradiation (w/sqm)');
grid on;
hold on;
plot(mean_DHI_jan,'b');
legend('GHI','DHI');

%Plotting the graph, June
figure(4):plot(mean_GHI_jun,'m');xlabel('time');
xlim([0 228]);ylim([0 600]);
set(gca,'XTick',(0:24:216));
set(gca,'XTickLabel',{'3:00','5:00','7:00','9:00','11:00','13:00','15:00','17:00','19:00','21:00'});
title('Hourly mean irradiation (w/sqm)');
grid on;
hold on;
plot(mean_DHI_jun,'b');
legend('GHI','DHI');
```

## A.5 Extracting GHI and DHI to calculate energy output

```
%--------------------------------------------------------------------------
%                         Extract GHI and DHI
%--------------------------------------------------------------------------
%January
%Extracting data at half past of every hour
i=7;%the first half past starting at index 7
j=1;%row index
while i<=length(mean_GHI_jan)
    HI1_day31(j,1)=mean_GHI_jan(i,1);
    HI1_day31(j,2)=mean_DHI_jan(i,1);
    i=i+12;%see the next 12 index
    j=j+1;%move to new row
end
%June
%same algorithm of the code for January
i=7;
j=1;
while i<=length(mean_GHI_jun)
    HI6_day27(j,1)=mean_GHI_jun(i,1);
    HI6_day27(j,2)=mean_DHI_jun(i,1);
    i=i+12;
    j=j+1;
end
```

# APPENDIX B: Solar panel data

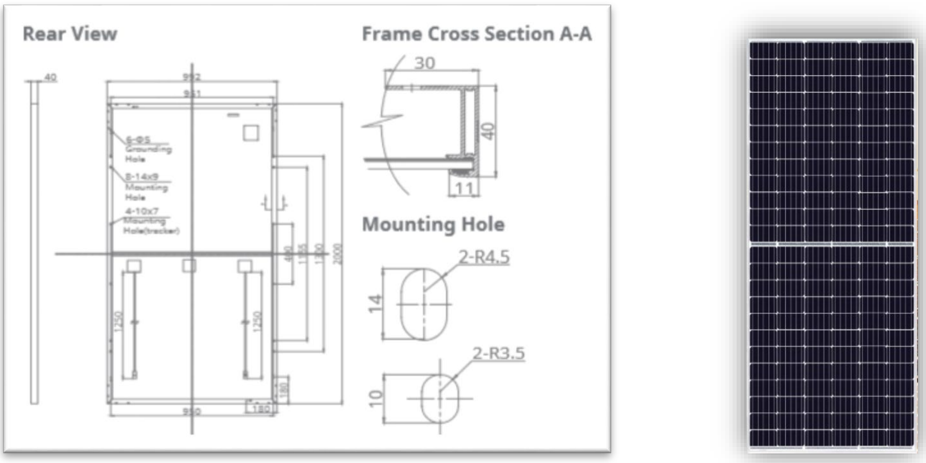


*Figure 16 Solar panel drawing from Canadian solar*

| Parameter | symbol | Value |
|---|---|---|
| **Manufacturer** | | Canadian Solar |
| **Module type** | | KUMAX (1500 V) CS3U-370MS |
| **Cell type** | | Mono-crystalline |
| **Cell arrangement** | | 144 (24 x 6) |
| **Nominal Max. Power** | $P_{max}$ | 370 W |
| **Opt. Operating Voltage** | $V_{mp}$ | 39.6 V |
| **Opt. Operating Current** | $I_{mp}$ | 9.35 A |
| **Open Circuit Voltage** | $V_{oc}$ | 47.4 V |
| **Short Circuit Current** | $I_{sc}$ | 9.85 A |
| **Module efficiency** | $\eta_{mo}$ | 18.65% |
| **Max. System Voltage** | $V_{max,mo}$ | 1500 V |
| **Temperature Coefficient** | $R_{Pmax}$ | -0.37% / °C |
| | $R_{Voc}$ | -0.30% / °C |
| | $R_{Isc}$ | 0.053% / °C |
| **Cell Temperature at NOCT** | $T_{c,noct}$ | 42±2 °C |
| **Air Temperature at NOCT** | $T_{a,noct}$ | 20 °C |

*Figure 17 Specification of solar panel*

## References


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