Sizing a Grid-Connected PV System to Power Kabaw Central Hospital

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Abstract:

This paper offers the sizing of a grid-connected PV power supply system. The case study site is Kabaw Central Hospital (Nafusa Mountain) in Libya. This paper deals with an estimated load is 1566.06 kWh / day energy output as a case study to find the optimum sizing and configuration for powering the load of the hospital. The system comprises monocrystalline PV modules rated at 365W, to obtain a total peak power of 255KW. Therefore, the site characteristics were studied, and all the loads of the central hospital were estimated. This paper's optimum fixed tilt angle was determined at 32°C to produce the maximum average radiation from the modules per year. The total active area and the total number of PV modules that could be installed were calculated. The best inverter model was identified and selected to generate a sinusoidal output current supply for the system. The percentage of energy covered by the PV system in this study was estimated in all seasons. The weather data on the site are obtained using PVsyst software.

Keywords: Sizing, Grid-Connected, PV System, Solar energy.

1. Introduction

As developing countries continue to advance their technologies and economies, industrialized nations have actively provided green and sustainable alternatives for these countries to consider. A photovoltaic system is an essential topic to research and study in Libya because solar energy potential is available [1]. As energy demand is expected to increase sharply, more oil and gas reserves will be consumed, leading to increased CO_2 emissions. [2]. Therefore, PV technology in Libya has huge potential as it has one of the highest solar radiation rates in the world. The average annual solar radiation is 2470 kWh/m2/year. Overall, the potential of solar energy resources is estimated at 140 thousand

TWh/year [3]. Therefore, solar energy could expand to meet demand increases in the loads. Hence, this research presents a simplified method for designing and sizing a PV grid connected to the base loads of Kabaw Hospital as a case study. The Grid-connected photovoltaic (PV) systems feed electricity directly to the power grid, operating in parallel with the conventional power supply. Their performance depends on the local climate, the orientation, the tilt of the PV array, and inverter performance. All these criteria have been studied in this paper [4]. Even if all of these criteria are met, other factors, such as dust, shade, clouds, and maintenance, will affect their efficiency. These are also, considered and called derate factors [5]. The number of solar panels needed in this research to power the load is done. This can be found by knowing these points [6]:-

1.Our daily power usage – kWh per day and derate factor that calculates the losses the system.
2.Average peak sun hours, specifically, is an hour during which the intensity of sunlight is 1,000 watts per square meter.
3. Actual power production per module
4. Determination percentage of energy covered by the design system; thus, we could compare the total power produced per day from these modules with the energy consumed per day to know how percentage of energy covered by the designed system.

2. Site Description

The selected site of this work was in kabaw city, which is located about 250 km south-west Tripoli capital city. The hospital building is composed of two floors with a flat rooftop area of about 4744 m^2. Figure 1 shows the rooftop map of Kabaw Hospital. This hospital building mainly includes the following：

- Nine administrative offices
- Eight outpatient clinics
- A delivery room
- An intensive care unit with four beds
- Two operating rooms
- Two male and female wards with a capacity of sixty beds
- A dialysis station with a capacity of fifteen beds

- A physiotherapy department
- A diagnostic radiology department (X-ray and endoscopy)
- Two emergency and first aid rooms
- A laboratory and a pharmacy
- A morgue
- Several warehouses for medical equipment and medicines
- A maintenance workshop, a kitchen, a restaurant, a dining hall, a laundry room (laundry), and a generator room.

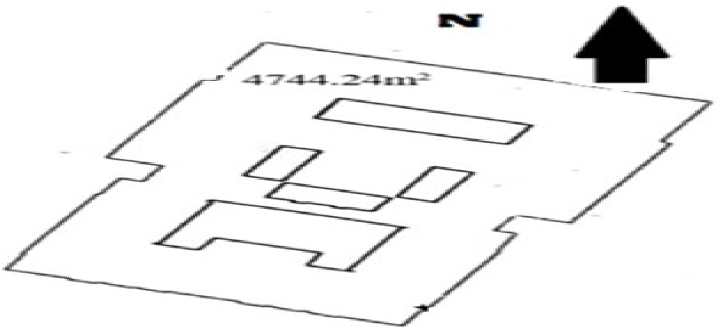

Figure 1: Rooftop Map of Hospital Building.

3. Site Characteristics

Libya is located between the longitudes 18.450 and the width 32.570 North, which it is exposed to the sun's rays throughout the year for long hours during the day. At the same time, the kabaw city lies between latitude and longitude, 31.8355 North and 11.3342 South. The interactive map for the site Kabaw– Libya is located as shown in Figure 2. Table 1 shows monthly solar irradiation levels, diffusion, and temperature in Kabaw City according to data obtained from PVsyst software by Kw/m2/day. All data was obtained using the PVsyst software Meteonorm8.1(1991-2010).

Figure 2: Interactive Map for the Site Kabaw – Libya

Table 1: The Monthly Average Global Irradiation for the Site

	Global [kWh/m²/day]	Diffuse [kWh/m²/day]	Temper. [°C]
January	3.01	1.22	10.3
February	3.76	1.59	12.1
March	4.89	2.01	16.9
April	6.10	2.45	20.8
May	6.77	2.65	25.6
June	6.99	2.73	28.9
July	7.30	2.36	32.1
August	6.87	2.26	31.5
September	5.69	2.09	28.1
October	4.47	1.60	23.5
November	3.52	1.22	16.9
December	2.82	1.10	11.5
Year	**5.19**	**1.94**	**21.5**

Which it observed that the solar irradiance is high (above the average) from April to September, with a peak in the month of July, while solar irradiance (below the average) in the rest of the year.

4. Sizing of PV Grid Connected System Procedure

The sizing of a PV grid-connected system involves site Insolation, load analysis, module, and inverter selection. The PV system proposed in this paper is to feed the largest possible percentage of Kabaw hospital loads by solar energy. It has planned to cover the other loads in case of a main power supply interruption by a diesel power plant.

4.1 Load Estimation (Load Profile)

The load profile is essential for the PV system sizing process since the variation of the irradiation and temperature affect the number of PV

panels and, hence, the inverter size. The hospital's electrical loads consist of various electronic devices, lighting loads, air conditions, medical equipment, office equipment, and different equipment. There are other loads for different seasons, and energy consumption varies according to daily activities. The primary results of a load inventory are quantitative estimates of the electrical loads and consumption of the facility. The electrical power of each device is indicated in watts (W), and its daily operating time is in hours (H).
The total energy consumption is indicated in kilowatt-hours per day (KWh/day), multiplying each load's power by its expected daily operation hours using the load estimation for the typical hospital. Which the loads in the hospital are calculated, their average daily consumption hours estimated and classified as shown in Table 2.

Table 2: Energy Consumed of Hospital loads

Average total Loads of:	Essential Loads (Kwh/day)	Percentage of daily consumption
Water Heater Loads	**169.6**	**10.83%**
Lighting loads	**189.8**	**12.12%**
Refrigerator, cooler, and freezer loads	**131.1**	**8.37%**
Laundry loads (washers and dryers)	**212**	**13.54%**
Air Conditioner Loads	**577**	**36.84%**
Electronic and Office Equipment Loads	**5**	**0.32%**
Medical Equipment and Devices Loads	**132.74**	**8.48%**
Water pump loads	**4.82**	**0.31%**
Other loads	**144**	**9.2%**
Total energy consumed	**1566.06**	**100%**

The results obtained in the table above show that the average total daily energy consumption at the site is 1566 kWh/day. Air conditioners represent the largest energy consumption, with a capacity representing about 36.85% of the total energy consumed. Washing machines (washers and dryers) consume the second largest percentage of energy, at 13.54% of daily consumption.

4.2. Module Selection

The performance, physical size, cost and other specifications of the modules are should be compared between the different types of modules before determining which type of module to use. The following table 3 represents the datasheet of GG1H-365 solar PV module that be used in this paper, where manufactured by CSI Solar Canada at 2020.

Table 3: Electrical Data of the CS3U-365MS-AG PV Module at STC

Peak Power (+/-%)	P_{max}	365W
Rate Voltage	V_{MP}	39.4
Rated Current	I_{MP}	9.28
Open Circuit Voltage	V_{OC}	47.2V
Short Circuit Current	I_{SC}	9.77A
Power Temp. Coefficient		-0.36%/^{0}C
Voltage Temp. Coefficient		-147 mV/ °C
Current Temp. Coefficient		4.9mA/^{0}C
Efficiency		20.63%
Module pure Area		1.98m*0.99m =(1.96m^2)

As mentioned in the above table if the rated peak output "watts" and de-rate in relation to the presumed NOCT of 32°C, 10°C higher than the rated operating temperature, since the peak output of the PV module drops by approximately 0.36% every 1°C higher. Therefore, at temperature 32°C the output of the PV module reduced by "**0.36 * 7= 2.52 %/^{0}C**".

4.3. Derate Factors

Every system has efficiency losses. High ambient temperature can cause a loss of voltage from an array of panels. Dust on the surface of the array causes power losses. Every component of a solar PV system has efficiency losses. System wiring involves efficiency losses. Online PV system sizing software will consider these losses when calculating system size. The solar industry refers to these factors as power reduction factors [5]. Thus, calculating these power reduction factors aims to determine the amount of AC power that will flow into the grid from the solar array, taking into account many environmental characteristics of the site as well as the system design and components selected [7]. Table 4 shows the default values for the overall DC to AC derate factor and the recommended adjustment to the derate factors.

Table 4: List of Derate Factors to Use for Grid-Connected System

Calculator for Overall-DC to-AC Derate Factor		
Derate Factors	**Derate Value**	**Acceptable Value Range**
Module power tolerance	0.97	0.88-1.05
The inverter and transformer isolated	0.95	0.88-0.98
Module mismatch	0.98	0.97-0.995
Diodes and connections	0.995	0.99-0.997
DC connection	0.97	0.97-0.99
AC connection	0.99	0.98-0.993
Contamination	0.95	0.30-0.995
System downtime	0.98	0.00-0.995
Shading	0.98	0.00-1.00
Overall DC-to-AC Derate factor		**0.787**

4.4 Orientation

In this research, we used the PVsyst V 7.4 simulation program to choose the best tilt angle for the solar module at the site at 32 degrees as shown in Figure 3. The amount of solar energy varies significantly depending on the tilt of the solar panels around the sun as shown in Figure 4 which shows the increase in the average annual solar radiation at the study site. Which the Comparative performance of the solar panel in case of horizontal placement of the panel and in case of placement at a tilt angle of 32 degrees facing south and at a deflection angle (azimuth angle) of 10 degrees facing west (depending on the building orientation). Table 5 shows numerical values of the average solar radiation for each month of the year and the effect of the module tilt on that.

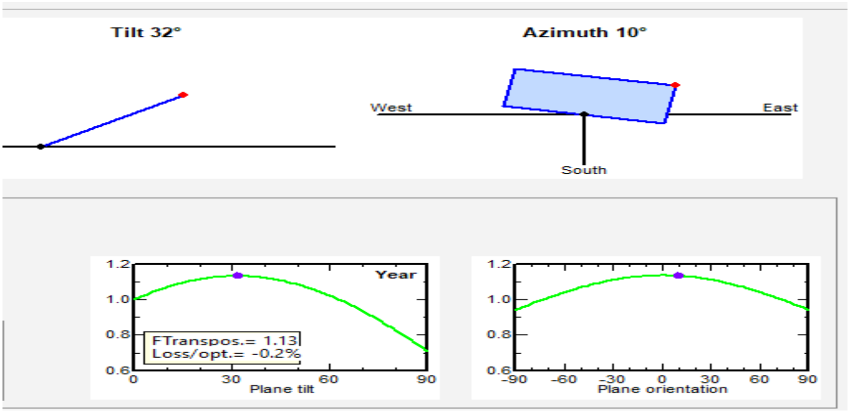

Figure 3: Optimal Fixed Tilt Angle Round the Year in Site

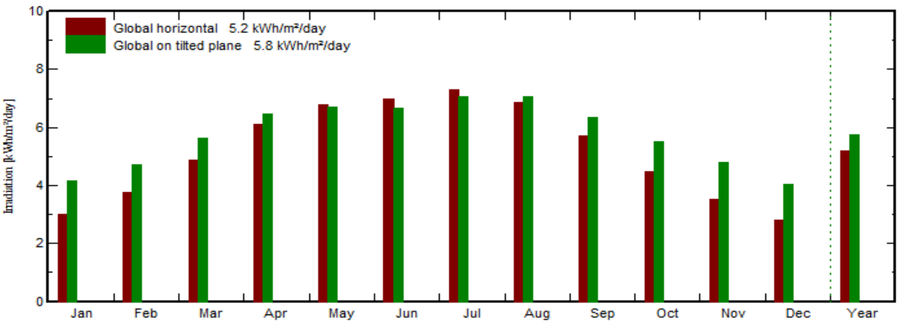

Figure 4: Monthly Solar Irradiation Levels in Kabaw (Hospital Site) City

Table 5: Different Panel Tilt and Irradiation Rates During a Year

Interval beginning	Global Horizontal kWh/m²/day	Fixed Tilt Angle kWh/m²/day
Jan	3.01	4.62
Feb	3.76	5.07
Mar	4.89	5.82
Apr	6.10	6.34
May	6.77	6.21
Jun	6.99	6.34
Jul	7.30	6.60
Aug	6.87	6.82
Sep	5.69	6.42
Oct	4.47	5.84
Nov	3.52	5.30
Dec	2.82	4.52
Year	**5.19**	**5.83**

4.5 Calculation of the Available Area for the PV System Capacity

When designing a solar system, it is often necessary to understand the length of the shadow, so that you can properly plan the spacing of the rows between the solar modules or between the modules and the roof wall. Therefore, both the sun's elevation and azimuth position must be accounted for when determining the length of a shadow. The raw sun position data that was used according sun path chart map for kabaw city as in Figure 5 by have used PVsyst software.

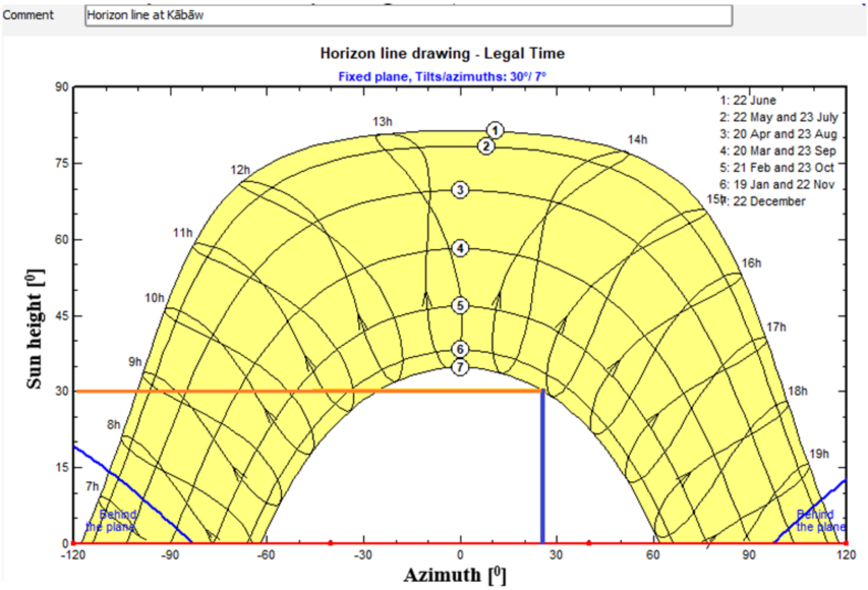

Figure 5: Sun's Path During a Year in the Site.

The angle of the sun's ray to the earth was determined to be 30^0 according to the ecliptic map, as shown by the orange line, from 8:50 AM morning to 3:00 PM, after nearly two hours of sun hour, on the 21st of December. The winter solstice in the Northern Hemisphere is the darkest day of the year (the shadow would be the tallest "worst case"). The blue line indicates the direction of the sun's angle, measured clockwise around the observer's horizon from the north. Hence, By knowing the area of the PV module that has been selected 1.98 m*0.99 m, it could find the length of the base for the tilt PV module angled by 32° on the horizontal axis and the height as shown in Figure 6 following:

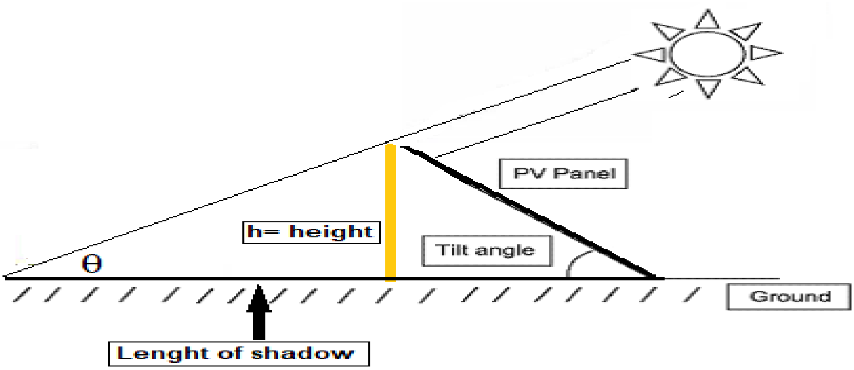

Figure 6: Calculation of the Length Shadow with Sun Rays Angle

The length of shadow = 0.99*cos 32^0 = 0.84 m

By using the Pythagorean Theorem Law, it could find the height of the stick is equal:

H= $\sqrt{0.99^2 - 0.84^2}$=0.52m

Therefore, to determine the shadow length using geometry as in Figure s

$$\tan\theta = \frac{Height\ (h)}{Lenght\ of\ shadow\ (L)} \quad (1)$$

$$L = \frac{h}{\tan\theta} \quad (2)$$

By knowing the area of the PV module that has been selected 1.98 m*0.99 m and the length of the base for the tilt PV module angled by 32° on the horizontal axis is 0.84 m, it makes it easy to find the safe distance between each row. Where it's nearly equal to 0.9 m in this work as shown in table 6.

Table 6: Calculations of Shadow Length

Places	Vertical height (h)	The tilt angle of sun rays(θ)	The Length of Shadow =(h)/tan
Optimal Tilt horizontal for PV modules at 30°	0.52m	30 °	0.9m

As a result of the last calculations that aimed to know the length of the shadow during the day between the solar modules or between the modules and the surrounding objects in general.

In addition, by knowing the area and measurements of the rooftop of the hospital (case study) where the solar panels are to be installed as shown in Figure 7. By Given, It could be estimated the total number of solar modules to be installed on the hospital roof can be calculated and their distribution organized based on the area measurements as shown in Table 7.

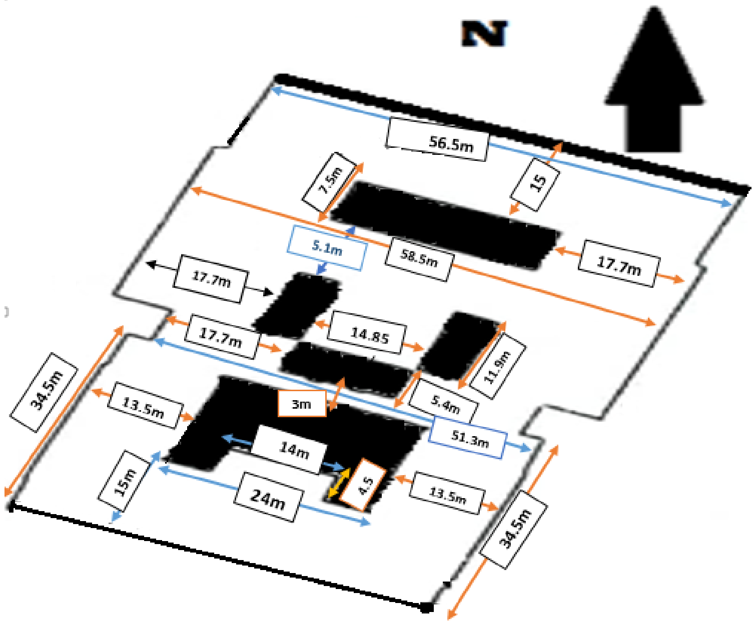

Figure 7: Hospital Rooftop Measurements and Dark Areas

Note: The black areas in Figure 6 indicate unsuitable locations for installing solar panels.

Table 7: Calculation of the Total Active Area

The Active Places Length * Width	No. Of PV Module in Each Row	No. OF PV Module in Each Colum	The Total of Modules Can be Installed
24m*15m	12	8	96
14m*4.5m	7	2	14
13.5m*34.5m	6	19	114
13.5m*34.5m	6	19	114
51.3m*3m	25	1	25
17.7m*5.4m	8	3	24
17.7m*5.4m	8	3	24
17.7m*11.9m	8	6	48
17.7m*11.9m	8	6	48
14.85m*11.9m	7	6	42
58.5m*5.1m	29	2	58
17.7m*7.5m	8	4	32

17.7m*7.5m	8	4	32
56.5m*15m	28	8	224
The total number of PV modules that can be installed = 895modules			
Total PV array size in kW= 895 * 365 = 326.675KW			
Total Active Area = 895 * 1.96 = 1754.2m²			

As shown in the table above, the total available active area is approximately 1754.2 m^2, which is equivalent to 37% of the total roof area. This means less than half of the roof area will be used for solar energy production in this research.

4.6 Choosing and Sizing the Inverter

The inverter is used to convert the DC power produced from the panel, to the AC power that is needed to power the AC loads in the hospital [8]. The array to inverter ratio can be found by dividing the power produced by the solar system by the maximum AC output of your inverter. For example, if your array is 7 kW with a 5800 W inverter, the array-to-inverter ratio is 1.20. The majority of installations will have a ratio between 1.15 to 1.25; inverter manufacturers and solar system designers typically do not recommend a ratio higher than 1.55 [9]. Therefore, the inverter specification selected in this paper is in Table 8.

Table 8: Inverter Selected Specifications Manufacturer 2023 SofarSolar

Type (SUNFOREST)	SOFAR 255KTL-HV D
Maximum PV Power	386 KW
Nominal PV Power	258 KW
Minimum MPP Voltage	500 V
Nominal MPP Voltage	1080 V
Maximum MPP Voltage	1500 V
Absolute max. PV Voltage	1500V
Maximum Input Current	600A
Nominal input Current	360 A
Nominal AC Power	255KVA
Maximum AC Power	KVA255
Maximum AC Current	184A

Nominal AC Current	184A
Grid Voltage	800V
Maximum Efficiency	99.01 %

The Inverter sizing depends on the input voltage from the PV generator. The output of the PV array is affected by climatic conditions, especially by variations in temperature. Therefore, we should estimate the range of the inverter input voltage variation due to the expected temperature variation of the selected site which is ranges “-5°C – 32°C” as given in the PVsyst software   The maximum and minimum module output voltage can be calculated by the following relationships [10]:

$$Module\ \boldsymbol{V_{oc-max}} = V_{oc}\ x\ [1 + (T_{min} - T_{STC})\ x\ (TkVoc)]$$
(3)

$$Module\ \boldsymbol{V_{mp-min}} = V_{mp}\ x\ [1 + ((T_{add} + T_{max} - T_{STC})\ x\ (T_k V_{mp}))]$$
(4)

Interpreting the equation variables,

V_{mp} The module rated V_{mp} at Standard Test Condition (STC) ▪

T_{add} The temperature adder value specific to an array mounting system, is equal to 32°C

T_{max} Maximum expected temperature in degrees.

T_{STC} The STC temperature at 25° C.

V_{oc} Module-rated open current voltage found on the module datasheet.

$T_k V_{mp}$ Module open current voltage temperature coefficient [%/°C], always expressed as a negative value.

Note: The datasheet shows T_{k}_V_{oc} = -147 mV/ , so, it could be convert this to a percentage = **0.147 V / 47.2 V = -0.00311 = -0.311%**.

$\boldsymbol{V_{OC-max}}$ Maximum module voltage corrected for the site's lowest expected ambient temperature [V].

$\boldsymbol{T_{min}}$ lowest expected ambient temperature for the site.

The maximum string size is the maximum number of PV modules that can be connected in series and maintain a maximum PV voltage below the maximum allowed input voltage of the inverter. So, to calculate the minimum string size, we need to calculate module V_{mpmin} first;

$$\boldsymbol{Module\ V_{mpmin}} = 39.4\ x \left[1 + \left((35 + 32 - 25)x\left(-\frac{0.36}{100}\right)\right)\right] = \mathbf{33.44V}$$

Hence, it could be calculate the maximum string size by the following relation:

$$\boldsymbol{Min\ String\ Size} = \boldsymbol{V_{min\_inverter}} / \boldsymbol{Module\ V_{mp\_min}} \qquad \textbf{(5)}$$

The V_{mp_min} is the inverter's minimum MPP voltage equal to 500V as in the datasheet of the inverter selected in this paper.

$$\therefore \boldsymbol{Min\ String\ Size} \cong \frac{500}{33.44} = \mathbf{14.95\ modules}$$

Lastly, we will round off the nearest integer number:

$$Min\ String\ Size \cong 15\ Modules$$

Then to calculate the maximum string size, it needs to calculate $\boldsymbol{Module\ V_{oc-max}}$ firstly as a last step;

$$\boldsymbol{Module\ V_{oc-max}} = 47.2\ x \left[1 + (5 - 25)x\left(\frac{-0.311}{100}\right)\right] = \mathbf{50.14\ V}$$

Then, we could start calculating the maximum string size as the following relation:

$$\boldsymbol{Max\ String\ Size} = Inverter\ V_{max} / Module\ V_{oc-max} \qquad \textbf{(6)}$$

The $\boldsymbol{V_{max}}$ is the inverter's maximum allowable voltage equal to 1080V as in the datasheet.

$$\therefore Max\ String\ Size \cong \frac{1080}{50.14} = 21.6$$

Lastly, we will round off the nearest integer number:

$$Max\ String\ Size = 22\ Modules$$

The allowed string size is between 15 to 22 modules. That means we have the flexibility to choose between 15 to 22 modules connected in series on one string, depending on the available installation space and system layout. The input DC voltage to the inverter is equal to the maximum or minimum string voltage which can be calculated by multiplying the number of modules in series by the maximum and minimum module voltage as follows:

$$V_{min\_inv} = 15 \times 33.44 = 501.6\,V$$

$$V_{max\_inv} = 22 \times 50.14 = 1120.42V$$

Note: We have chosen to install 22 PV modules in string in our system design to reduce the number of modules in parallel for lower cost and minimize losses. As therefore:

The number of modules in parallel

$$= \left[{No.\ of\ total\ PV\ modules}/{No.of\ PV\ modules\ in\ strings}\right]$$

(7)

$$\therefore No.of\ parseasonallel\ strings = \frac{895}{22} = 40.68 \cong 41\ Modules$$

Thus, the total of PV modules that we install in the system will be;

$$= 22 * 41 = 902\ Module$$

That is more by 7 modules depending on the last calculation as in table 7. Therefore, we could modify to install them in the system by choosing the last row of modules and placing them over them, in which the extra height (shadow) of that row chosen does not affect the other rows. Based on the previously mentioned data, the daily PV production in kWh and % Energy covered by the design system could be estimated in each seasons as in Table 9. The temperature losses and reduction factors of the system were taken into consideration.

Table 9: Calculate Daily PV Production in kWh & % Energy covered

Average Peak Solar Irradiation By(KW/m2/day)	X	Daily PV Production in(kWh) (902 *365)	X	Temperature losses%	X	Derate Factor	=	Daily PV Production in kWh	% Energy Covered by the Design System
In winter = 4.6	X	329.23	X	0%	X	0..787	=	1192	76.1%
In Spring= 6.15	X	329.23	X	%0	X	0.787	=	1593.5	101.75 %
In Summer = 6.6	X	329.23	X	%2.6	X	0.787	=	1665.6	106.6 %

In Autumn =5.77	X	329.23	X	%0	X	0.78 7	=	1495	95.5%
The Average during a year = 5.78	X	329.23	X	0.65%	X	0.78 7	=	1488	95%

The percentage covered by the PV system is between **106.6%** in summer and 76.1**%** in winter. Where the higher energy percentage will be covered by the system in the summer months, which has the highest average solar radiation. The lowest part is in the winter seasons, which have the minimum average solar radiation as could have noticed that from above in Table 9. However, the average percentage covered by the PV system during a year is 95%.

5 System Sizing Specifications

When sizing a grid-connected inverter to operate with a PV array both the inverter's overload capacity and its efficiency characteristics must be taken into account. The designed system size and specifications for a 255-kW power plant are shown in Table 10. The total value of the DC and the voltage produced from the whole PV system can be calculated using rated module current I_{MPP}, rated module voltage V_{MPP}, and the number of modules connected in string and parallel respectively:

$$\boldsymbol{V_{DC}} = \boldsymbol{V_{MPP}} * \text{ (No of series-connected modules)} \quad (8)$$

$$= 39.4v * 22 = 866.4\,V$$

$$\boldsymbol{I_{DC}} = \boldsymbol{I_{MPP}} * \text{ (No of parallel-connected modules)} \quad (9)$$

$$= 9.28A * 41 = 380.5\,A$$

Thus, the DC voltage at the DC link is adjusted to maintain a constant at 866.4 V resulting in fixed DC power delivered to the DC/AC inverter. Table 10 PV Power Plant Specifications.

Table 10: PV Power Plant Specifications

Plant capacity	KW 2.329
Voltage output	866.4 V
Current output	380.5V
Derate Factor &Average Temperature losses	0.787*0.977 = **0.769**

No of modules	902
Effective area	1754.2m^2
Array Type	Fixed
Array Tilt	32^o
[redacted]	
Type	Monocrystalline
Rated power	365W
Rated Voltage (V_{Mpp})	39.4 V
Rated Current (I_{MPP})	9.28A
Efficiency	20.66%
Temperature	25 ^{0} C
Module Area	1.96 m^2
[redacted]	
Type (SUNFOREST)	SOFAR 255KTLHV
Maximum PV Power	386 KW
Nominal PV Power	258 KW
Minimum MPP Voltage	500 V
Nominal MPP Voltage	1080 V
Maximum MPP Voltage	1500 V
Absolute Max. PV Voltage	1500V
Nominal input Current	360 A
Maximum Input Current	600A
Nominal AC Power	255KVA
Maximum AC Power	KVA255
Maximum AC Current	184A
Nominal AC Current	184A
[redacted]	
Number of phases	3-Phases
Voltage rating	400 volts
Frequency	50 Hz

Conclusion

The sizing computations for a grid-connected PV system are presented. The results showed that the sized grid-connected PV system supplied about 1488kWh / day on average during a whole year. That is, by a percentage of covered equal 95%. The energy is injected into the inner network of the hospital. In general, the percentage covered by the PV system ranges between 76.1 % in winter to 106.6 % in summer, depending on peak sun hours in each season. Therefore, it is planned to cover other loads, especially in winter, if power is interrupted from the main power source by a diesel generator. That makes our grid-connected PV system work as a Micro-grid. In addition, the power surplus produced from this system, especially, in summer and spring, will be used to support the public electricity grid.

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