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Design of a 50 kW solar PV rooftop system

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Abstract

Renewable energy resources become very popular and commonly used nowadays. An example of a clean renewable energy resource is the energy generated using photovoltaic (PV) systems. As a result of using PV as a renewable energy resource, components of PV such as an inverter become widely used for this purpose and in order to enhance the maximum obtained power from PV, different methods were used to achieve the desired power, where it become a very considerable to use different methods to achieve desired maximum power received from PV. The main goal of this manuscript is to introduce the idea of using photovoltaic system, along with its components, (sizing of arrays, charge regulator ratings, inverter ratings and other related information), for a specific load, (Majan Electricity Company (MJEC) administration building – Sohar – Sultanate of Oman), to achieve a design generates power up to 50 kW from solar PV system. MJEC Company provided details of the available area of the rooftop. Solar irradiation data will be utilized to estimate the annual energy output as well and the cost per kWh of electricity generated from a specific PV system using RETSCREEN software. Economic indicators such as internal rate of return, the payback period, the net present value, the annual life cycle savings, and the cost renewable energy production will be considered as well.

Keywords: Renewable energy sources, PV, inverter, power system, maximum power

1. Introduction

Nowadays many issues appear due to the fact of using fossil fuel as a primary resource in generating electricity. The solution to such issues can be eliminated or reduced by means of using a renewable energy such as a solar power system. The first issue that is related to use of fossil fuels is the global warming, where the increase of using fossil fuels such as oil and natural gas in generating electricity resulted several health and environmental problems. Natural gas gives off 50% of the carbon dioxide, the principal greenhouse gas, released by coal and 25% less carbon dioxide than oil, for the same amount of energy produced. Coal contains about 80% more carbon per unit of energy than gas does, and oil contains about 40 percent more [1]. Global warming has many effects such as earth temperature increase, sea level rise. Second issue is the air pollution. A lot of pollutants are produced by fossil fuel combustion that is used to produce electricity such as Sulfur oxides, and hydrocarbons. In addition, total suspended particulates contribute to air pollution can combine in the atmosphere to form tropospheric ozone, the major constituent of smog. Third issue, is the cost of the fossil fuel, the electricity that produced by the fossil fuel process is more expensive than the electricity produced by the renewable energy such as solar power. In fact, the estimated costs of building new coal plants have reached $3,500 per kW, without financing costs, and are still expected to increase further. This would mean a cost of over $2 billion for a new 600 MW coal plant when financing costs are included [2]. Another issue that is noticeable nowadays

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is the water and land pollution. Water spills causes harm to plants and animals life. Coal mining also contributes to water pollution. Coal contains pyrite that is a Sulfur compound [3]. On the other hand, Photovoltaic offers consumers the ability to generate electricity in a clean, quiet and reliable way [4]. To increase the PV utility, dozens of individual PV cells are interconnected together in a sealed, weatherproof package called a module. Modules are connected either in series or parallel. The flexibility of the modular PV system allows designers to create solar power systems that can meet a wide variety of electrical needs [4]. There are two broad categories of PV system: Grid-tied systems which are connected to the public electricity grid and stand-alone systems which are isolated system [5]. The grid-tied PV connected to the power grid at all times and do not require battery storage. A solar PV system can provide power to a home or business, reducing the amount of power required from the utility; when the solar PV system power generation exceeds the power needs, then the surplus power automatically will be pumped back into the grid. A solar PV system will not operate during a power outage unless it has battery backup [8]. Standalone systems are totally self-sufficient with no connection to the utility grid system. They generate electricity during daylight hours, and store excess for night time use [9].

In this paper, a design up to 50 kW solar PV system to the rooftop of a head office of MJEC company – Sohar – Sultanate of Oman is introduced where necessary components between the PV system and the load for the required design are identified. The expected cost, engineering standards and realistic constraints of the required design are studied by using RETSCREEN software for energy and cost model.

2. Components of PV System

The PV system consists from main part which is PV cells which produces the power but there are other components are also needed to, control, convert and store the energy such as PV modules, batteries, charge controllers, and inverters. The PV system and its components are detailed in the block diagram shown in Fig. 1.

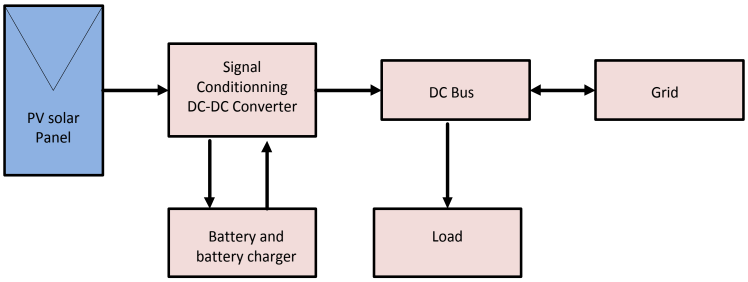


Fig. 1. General block diagram of PV system

2.1. PV modules

The PV modules are a group of many cells connected either in series to increase the voltage or in parallel to increase the current. The number of cells in the model is governed by the voltage of the module. The nominal operating voltage of the system usually has to match to nominal voltage of the storage system [10]. PV modules are categorized as either crystalline or thin film, and they are judged on two basic factors: efficiency and economics [10]. Crystalline modules are categorized into two main types: mono crystalline and polycrystalline. Mono crystalline modules are made from a large crystal of silicon. They are the most efficient type in converting sunlight into electricity with an efficiency reaches 18 % [11]. Also, this type is more expensive than polycrystalline. Polycrystalline modules are the most common type of the PV modules and they are less efficient than the mono crystalline modules and less expensive. The efficiency of polycrystalline modules are rated from 13 % to 15 % [11].

2.2. Batteries and charge controllers

The batteries are used to store electric energy and to be used when there is no sunlight. There are two main types of the batteries that are used in the PV system: Lead Acid battery and Deep Cycle battery. The batteries in most common use are lead-acid type because of their good availability and cost effectiveness and also it is capable of producing high currents [12].

A charge controller is a current-regulating device that is placed between the solar array output and the batteries. These devices are designed to prevent the batteries from being overcharged or overly discharged [10]. Some charge controllers use on/off control using pulse width modulation. It works to slowly reduce the amount of charge that follow into the battery as the battery approaches its fully charge stage [14].

2.3. Inverters

Inverters are used to convert the battery or solar panels output to ac quantity that can be used either to be connected to the grid or used by electric devises. There are three main types of inverters, namely; stand-alone inverters, it runs the electrical devices within the system but it cannot be connected to the grid. Grid-tie inverters, it can be connected to the grid and they are designed to automatically disconnect and shut down when there is a loss of utility supply but they do not provide backup power during power outages [15]. Battery backup inverter, it is a combination of the previous two types. They provide the electricity needs by the system and they can also be connected to the grid [15].

3. Maximum Power Point Tracking (MPPT)

In order to improve the efficiency of solar cells and generate Maximum Power Point Tracking (MPPT) should be used. It is an electronic system that operates module of the PV in a way such that it allows the module to produce all capable power. MPPT increases electrical efficiency of PV and helps to reduce number of solar panels, required area for installing PV arrays for producing the desired output. Regarding the Maximum Power Point (MPP), an experiment was conducted and the main objective was to determine the characteristic curve of the PV module, and to be able to locate the MPP of the PV module, by means of using PV module cells. The open circuit voltage of the PV is measured and followed by measuring the PV short circuit current. A variable resistance which resembles the load across PV panel was varied in steps, and for each corresponding value of the load, the voltage across the load and current through the load was measured. These results were used to obtain the characteristic curve of the PV module. Fig. 2 shows PV characteristic curve. As the resistance of the load increases, the produced current decreases and the output voltage across the PV panel increases. Hence, the relationship between the produced voltage and current is inversely proportional as it can be noticed in the characteristics curve of PV from Fig. 3. It can be noticed from Fig. 3 that there is a point in the curve where the output voltage and output current produces the maximum output power which represents MPP (12.1 V, 2.9 A, 35 W).

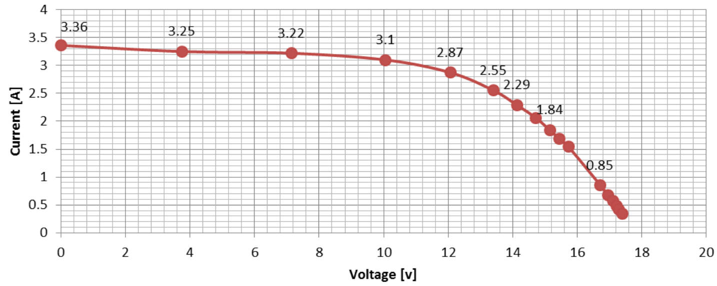


Fig. 2. PV output voltage vs. PV output current characteristics.

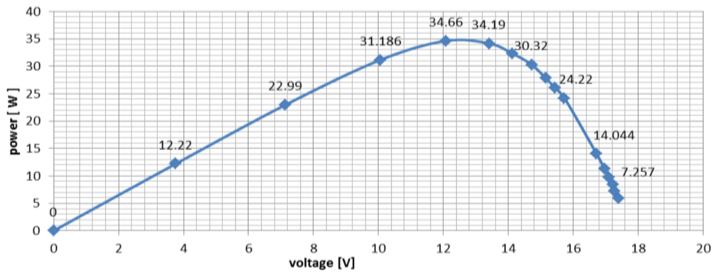


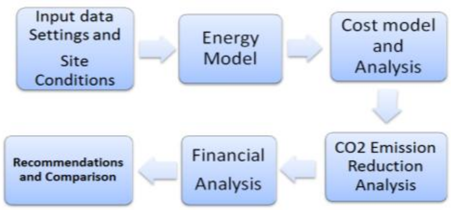
Fig. 3. Voltage vs power curve according to different values of the load resistance.

4. Proposed System Design

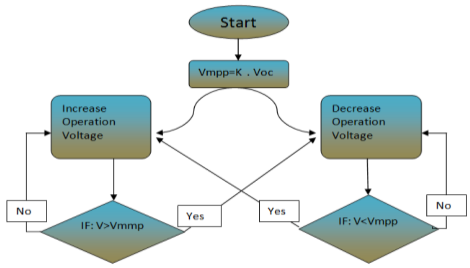
The main target is to design up to 50 kW PV solar system. It is required to obtain the produced energy, the cost and financial analysis, the reduction of CO_2 emission by means of using the RETSCREEN software. In addition, determination of effective area that is required for the PV panels' installation. The output results and/or the product will be compared to MJEC Company given data which is listed in the appendix. RETSCREEN is an Excel-based clean energy project modeling and analysis software tool such that it helps the owners to determine the financial viability of potential renewable energy, energy efficiency and cogeneration projects. It is also allows to verify the ongoing energy performance [13]. The Flowchart of RETSCREEN data obtaining process is shown in Fig. 4 (a) while constant voltage method for MPP algorithm to be used for the design process is shown in Fig. 4 (b).

4.1. Design requirements

Before starting with RETSCREEN modeling and analysis, it is required to select the main components: PV module type, and inverter as well as PV system mounting requirements and dimensions according to MJEC requirements. The rooftop map of MJEC company head office with dimensions is given in the appendix



(a)



(b)

Fig. 4. Flow charts: (a) RETSCREEN software of data obtaining process and (b) constant voltage method for MPP algorithm to be used for design process.

Table 1. PV module parameters and ratings [14]

Electrical characteristics	
Open Circuit Voltage (Voc)	38.00 V
Maximum Operating Voltage (Vmp)	30.40 V
Short Circuit Current (Isc)	8.98 A
Maximum Operating Current (Imp)	8.22 A
Module Efficiency	15.37%
Maximum Power in STC (Pmax)	250 Wp
Operating Temperature	-40 ℃ ~ + 85 ℃

Table 2. PV module specifications and dimension [14]

	Specifications and dimensions
Cell	Polycrystaline Silicon solar cells 156 mm×156 mm/6 inch
Number of cells	60 (6×10) pcs
Module dimension	1640 mm × 992 mm ×50 mm / 64.6 inch ×39.1 inch×2.0 inch
Weight	19.6 kg
Front glass	3.2 mm tempered glas
Frame	Anodized aluminium alloy
Protection degree	IP65
Plug connector protection degree	IP65/IP67 (MC4)
Bypass-Diodes	6 pcs (IEC)/3 pcs. (UL)
Maximum fuse current rating	15 A
Type of connector	MC4, MC4 compatible, MC3 compatible, 0-1394462-4/6-1394461-2
High Efficiency	17.4 %
Warranty	10 years for 90 % performance and 80 % for 25 years
Grid connection	ON/OFF grid and easy installed

A. PV module selection

The selected PV module is BYD-250P6-30 manufactured by BYD solar company [14], where the module parameters and ratings is included in Table 1. This module agrees with MJEC requirements [14]. The maximum power of this module is found to be 250 W, hence it requires 200 module to design 50 kW PV power system. This module is able to be used for on grid utility systems [14]. More specified information is illustrated in Table 2 [14].

B. Inverter selection and manufacture type

The module name of the selected Inverter is called TRIO-27.6-TL-OUTD a three phase grid-tied type of inverter manufactured by Aurora company [15]. Table 3 describes some of the parameters of this inverter where it contains two independent MPPTs and the efficiency is as high as 98.2 %. In addition, the maximum dc input power for each MPPT is 16 kW, so each inverter can receive up to 32 kW as a maximum input dc power, while its capacity is 30000 kW. Hence, for a 50 kW design it may require two inverters of such module type [15].

Table 3. Inverter parameters and ratings [15]

Number of Independent MPPT	2	Maximum efficiency	98.2 %
Maximum dc input power for each MPPT	16 kW	Rated ac power	27.6 kW
Maximum ac output power	30 kW	Rated ac grid voltage	400 V
Maximum ac output current	45 A		

4.2. RETSCREEN results and energy model results

The selected settings and input data to RETSCREEN software is illustrated in Table 4. The settings will produce the total area to be used for installing PV panel. According to the input settings, the results show that proposed energy model exports 85 MWh to the grid. It is well known that solar PV panel operation does not cause any pollution or in other words, it does not emit greenhouse gases. RETSCREEN software helps to determine how much emission can be reduced when using a clean energy resource. The results of the emission reduction analysis can be used to calculate how much income can be gained from reducing the GHG emission. Moreover such results can be used for comparison purposes between the emissions being produced from different fuels. The transmission and distribution losses were set at 10 % resulting a GHG emission factor of 0.867 tCO2/MWh [16]. The results of emission reduction for producing 85 MWh annual energy results for a value of base case GHG emission reduction is 73.7 tCO2 which includes the GHG emission factor that considers the T&D losses. While the actual annual GHG emission reduction is found to be 66.3 tCO2, if T&D losses is not considered and keeping the GHG emission factor equals to 0.78.

Table 4. Input settings for 50 kW PV system design to RETSCREEN

Type	Poly-Si	Type	Poly-Si
Power capacity	50 kW	Miscellaneous losses	5 %
Manufacturer	BYD Solar Company	Inverter efficiency	98.2 %
Model	BYD-250p6-30	Inverter capacity	30 kW
Efficiency	15.4 %	Capacity factor	19.4 %
Solar collector area	325 m^2	Annual electricity exported to the grid	85 MWh

4.3. Cost and financial analysis results

It is required to verify the cost of each major component of the proposed system in order to observe financial analysis including financial viability to obtain the net present value results, cost to benefit ratio, simple pay back duration and cumulative cash flow over years. In RETSCREEN cost and financial analysis, for financial parameters, the project period input were set to 25 years. The major components taken into an account in terms of their costs are the panels of PV, inverters and mounting structures that were used to install the PV panels. The cost is found to be 168.63 OMR per PV module [17]. Since it is required to have 200 modules to design 50 kW PV system, then the cost would be 33726 OMR for 200 modules. The cost per inverter unit is 2053 OMR but in the proposed system two inverters are required so, inverters cost is 4108 OMR. The cost of mounting structure is necessary to be considered as well. It was found the price of mounting and installation is 0.55 $/W which is equivalent to approximately 0.210 OMR/W [18]. Hence, it will cost approximately 10550 OMR to install 50 kW PV modules. The total cost for 200 modules and two inverters are calculated under power system cost which is 37832 OMR. Hence, the total initial cost including mounting and structure is 48382 OMR. The Panels may require annual maintenance and service so the labor charges were assumed to be 200 OMR per year. According to MJEC the average electricity production rate is nearly 0.025 OMR/kWh [19]. Hence the exported electricity income can be calculated by multiplying the electricity production rate per kWh times the annual energy exported in which was found to be 2125 OMR. The GHG reduction credit rate in OMR/ tCO_2 is found to be approximately 7.7 [20]. Based on the net annual GHG reduction which is approximately 74 tCO_2/year, the two resulted annual GHG reduction incomes are approximately 567 OMR. While, the net GHG reduction over 25 years was found to be 1842 tCO_2.Therefore the total annual income and savings is 2692 OMR. Based on the obtained incomes from both exported electricity and GHG reduction, the financial viability results are summarized and included in Table 5.

Since the overall cost of this project is very high, so in duration of 25 years with discount rate of 7.5% [20] and based on the incomes the net present value will be -21405 OMR. While the internal rate of return (IRR) was found to be less than the discount rate which is 1.7 %. In addition, the benefit to cost ratio (B-C) is found equals to 0.56. Since the discount rate is higher than IRR and the (B-C) is less than 1, this project is not considered as a feasible project. Hence, it is not economical project. According to Fig. 5, it takes nearly 19.4 years of project operation to start receiving pay back and the cumulative cash flows becomes positive by then.

Table 5. Financial visibility summary results for discount rate equals to 7.5 %

IRR	1.7 %	Annual life cycle savings	-1920 OMR/yr
Payback	19.4 years	Benefit-Cost (B-C) ratio	0.56
Net present value (NPV)	-21405 OMR	Energy production cost	47.56 OMR/MWh

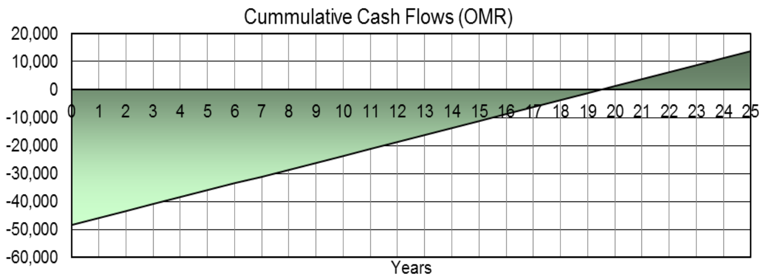


Fig. 5. Cumulative cash flows (OMR) of 50 kW PV power system operating for 25 years.

Table 6. Financial visibility summary results for discount rate equals to 7.5 %

IRR	11.2 %	Annual life cycle savings	1480 OMR/yr
Payback	8.2 years	Benefit-Cost (B-C) ratio	1.34
Net present value (NPV)	16494 OMR	Energy production cost	47.59 OMR/MWh

For a purpose of comparison, a study case was conducted by assuming the average electricity production rate to be $0.17/kWh [21] which is equivalent to 0.065 OMR/kWh, this is the price of electricity generated by crystalline type of PV in early 2012 in USD [21]. Based on that, the exported electricity income becomes 5525 OMR. Then, keeping the annual GHG reduction income the same which is 567 OMR, the total annual income and savings will be 6090 OMR. Then, the new financial viability results are summarized in Table 6, where the net present value is found 16494 OMR. While the internal rate of return (IRR) was found to be more than the discount rate which is 11.2 %. The benefit to cost ratio (B-C) is found equals to 1.34. Since the IRR is become higher than discount rate and the (B-C) is more than 1, the new results showed an improvement of this project in economical point of view. It is much more economical and more feasible compared to the previous results. This means, the low electricity production rate which was 0.025 OMR/kWh was causing the project to be considered non feasible. In addition Fig. 6 shows that pay back duration becomes 8.2, which indicates feasible results compared to previous financial viability.

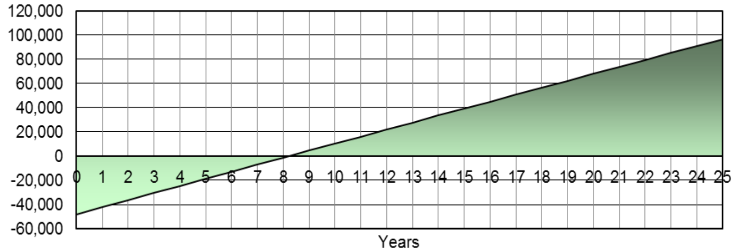


Fig. 6. New cumulative cash flows OMR of 50 kW PV system for 0.065 OMR/kWh.

4.4. Effective PV area design

According to RETSCREEN energy module results, for designing a 50 kW solar PV system it requires an area of 325 m^2 for installing PV panels; however RETSCREEN energy model does not consider the constraints that might affect the available area for PV panels installation such as the shaded area to be avoided, spacing between PV panels which in case of multiples of panels it cannot be neglected. According to MJEC requirements, the constraints are spacing distance between two PV panels 0.15 m. The distance between each set is 1.5 m. Also, 1.5 m must be distanced from rooftop edge for safety purpose. The rooftop of MJEC company head office shown in the appendix has a total area approximately 600 m^2. The rooftop has a storage room centred in the middle of roof area; therefore shading area must be estimated in order to avoid setting the panels on the shaded area. The required area must satisfy the estimated area along with its constraints. For designing 50 kW PV system by means using a panel produces an output of 250 W, it requires to have a total 200 panels. Table 2 shows the selected PV module dimensions, where each panel has a length of 1.64 m, and width of 0.998 m, hence the area of one panel is 1.63 m^2.

The process of estimating whether if 200 PV modules would fit on 600 m^2 rooftop or not begin with calculating the available area considering the shaded area, spacing between the modules, safety distance between the modules on rooftop boundaries or edges and separate distance between each set of an array. For first iteration, the spacing distance was selected to be 0.15 m. As requested from MEJC, it seems the separating distance between each PV set is 1.50 m. The safety boundary distance was also requested to be 1.5 m from the edge of the rooftop. Then, shading area that will be caused by the storage room is estimated to be 3m to 4 m distance away from the room in order to avoid losses caused by the shadows. The rooftop of the storage room can be used as well to install few panels on the top. After conducting some calculations regarding the area, and reducing the boundary edges and shaded area it was found that the available area is approximately 360 m2. Next step was to arrange 200 PV modules such way that it accommodates the available useful area and considering array separation distance constraint. This was done by dividing the rooftop into seven sectors and roughly the panels were sketched according to the area of each panel. Each array set was assumed to have 10 modules, with separation of 1.5 m between each set and considering all affecting constraints; however some sectors may not able to hold 10 arrays as a set. In addition, the modules were placed to be facing south direction since Oman is located on the North of equator line so the direction of solar radiation to receive most when facing south. Based on the pervious requests and available area, only 100 modules were able to be placed.

The 50 kW design requires a total of 200 modules if each panel produces an output power of 250 W, so the 100 estimated module results a design of 25 kW only. In that case, second iteration was performed by minimizing the limitations. The spacing distance between each panel was selected to be 0.1 m, while the distance between each set or row was selected to be 1 m and the boundary or distance from edge of the rooftop was kept at 1.5 m. This results in an available area of 360 m2. The PV panels were arranged and it was found only 124 panels can be accommodated on the estimated area when making considerations of this iteration, which produces a total of 31 kW.

Few more iterations were carried in order to see if 50 kW is applicable to be designed on that rooftop. The most possible minimized limitation was performed for having the spacing distance equals to 0.1 m, while the edge distance was set at 1 m. The separation distance was selected to be 0.5 m, and the distance avoids the shading caused by storage room was kept the same (3 - 4 m). Based on that, the available area was found to be 402 m^2 for 8 sectors with 171 modules. It seems for this iteration, 29 modules cannot be installed; hence this will result of having a design of 42.750 kW which is an output of 171 modules for 250 W per module.

5. Conclusion

As requested from MJEC, It is required to design a 50 kW solar PV power system located or mounted on the rooftop of MEJC head office building by means of determining the engineering standards and realistic constraints of the design. RETSCREEN software was used to provide necessary data regarding the cost and financial analysis to determine the annual energy produced and the amount of GHG reduction according to the produced clean energy. From the energy module, required area for installing such system was verified; however after several iterations it was found designing such system on the given rooftop area was not possible and difficult to approach due to limitations and constraints that considers separations, spacing distances and shadowing effect. From financial viability results, this project is not considered as an economical project due to IRR was found to be less than discount rate, and the simple payback period was found to be very long. However, electricity production controls the feasibility of this project.

Acknowledgement

The authors would like to acknowledge the support of Majan Electricity Company for supporting and providing the necessary data.

Appendix: Data Requirement by MJEC

A.1. PV Module

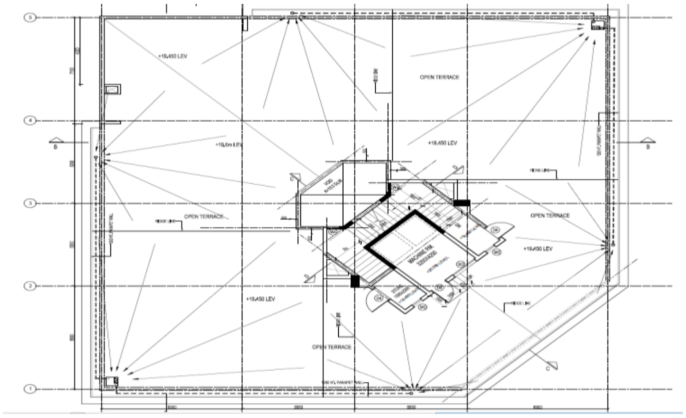
- PV generator (Polycrystanline Module technology)
- Efficiency level ≥ 15 %
- Power class ≥ 245 Wp
- MC4 connector
- Anodized Aluminum alloy frame with front technologies.
- It must have certificate approval from ISO9001: 2008, ISO4001:2001 and IEC61215, IEC61730, UL1703
- Corrosion resistance, ammonia & salt, with positive power deviation of 0 – 3 %
- Product warranty ≥ 10 years
- The module will be mounted on the flat roof top with a 1.5 m distance of each raw to avoid shadow losses.

A.2. Inverter Required Parameters

- The inverters are mounted on wall or mounting structure.
- The installation site has to be qualified for fail-safe operation.
- Inverter (Decentralized system design and Multiple PV modules assigned to string inverters. 50 Hz/400 V, 3 phase, transformer less topology, IP 65, more than or equals to 97.8 % Euro efficiency, more than or equals to 2 number of MPPT.

- Certificates and approvals from EN 50178, AS/NZS3100, AS/NZ 60950, EN61000-6-1, EN61000-6-3, EN61000-3-11, EN61000-3-12.
- Enel guideline VDE 0126-1-1, G59/2, EN 50438, RD 1663, AS 4777.
- Product warranty => 10 years.

A.3. The rooftop map of head office MJEC company



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