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Photovoltaic Power Stations (PVPS)

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Abstract- Qatar declared that by 2020 solar energy would produce at least 2% of its total generated electric power (EP). The known solar power plants EP at utility scale level are concentrating solar power (using parabolic trough collectors, linear Fresnel collector, and solar tower), photovoltaic (PV), and integrated solar combined cycle using fossil fuel (natural gas) besides solar collectors.

EP generation by PV is reliable, clean, well proven, and matured technology, with 25 years warranties on solar panels. PV is the direct conversion of solar radiation (sunlight) into direct electric current by semiconductors that exhibit PV effect. The PV can be applied to large scale power plants called photovoltaic power station or solar parks. A solar park is connected to the grid, and thus supplies its bulk produced EP to this grid. Transfer solar energy directly to EP is achieved without using moving parts means very low maintenance and operation requirements. Once a solar park is installed (with relatively high cost compared to conventional power plat such as combined cycle), the operating costs with no fuel supply are extremely low compared to conventional power plants.

This paper presents the technology and economics of the PV power station. It outlines the main components of the PV power plants including the solar PV modules, module mounting and tracking systems, inverters (or converters), and step-up transformers. It reviews the materials of the PV cells, the PV cells degradation, and the existing PV power plant. Utility PV power plants around the world were reviewed.

PV panel are extensively used for small-distributed power generation used in homes and in remote areas. One of the advantages of building solar parks in Qatar (and other GCC) is the coincide of its power output with the high air conditioning electric power demand in hot summer days. The GCC is the Gulf Co-operation countries including Saudi Arabia, United Arab Emirates, Qatar, Oman, and Bahrain. Recent reductions in photovoltaic cells cost are the driving force behind the trend of building more solar parks worldwide.

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Mohamed A. Darwish [α], Hassan K. Abdulrahim [σ] & Adel O. Sharif [ρ]

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The System Advisor Model (SAM) software developed by National Renewable Energy Laboratory (NREL) gives the total direct capital cost of the 20 MW PV plant as $88.0 million (M), and total installed cost as $ 97.202 M; or $4.86 M/MW. This is almost half the cost of the CSP using by parabolic trough plants. The LEC, as given by the computer program is $0.16/kWh. The main disadvantage of the PV power station is non-dispatch ability.

I. Introduction

Production of Electric Power (EP)by photovoltaic (PV) is clean well proven technology, that are applied in large scale Power Plants (PPs) called PV Power Station (PVPS), or solar parks. The bulk of the generated EP by the PVSPS is supplied to the electric grid output, Fig. 1, [1].

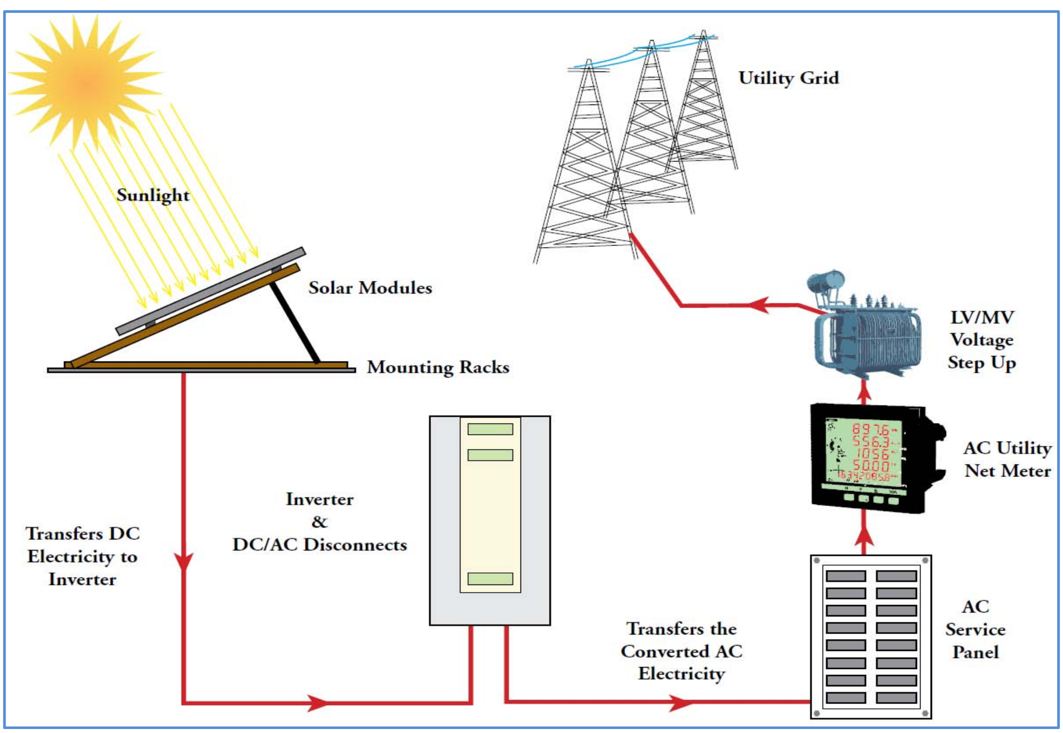

Figure 1 : Overview of Solar PV Power Plant, [1]

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The economy of PVPS is improving by time as shown Fig.2a, [2]; and solar cell production is increasing, Fig.2b, [3]. The capacity of the PVPS is on the rise worldwide, Fig. 3a, [3] due to the decrease of PV cells' cost, Fig. 3b, [4]. By the end of 2013, the installed capacity of PVPS reached 136 GW, see Fig. 3a. The PVPS was rated the third in terms of capacity of the renewable energy power plants after hydro and wind in 2011, [3]. This capacity is almost doubled between 2011 to 2013 due to PV cells continuous falling costs and increasing cost of fossil fuel used in conventional power plants. It is estimated that solar module prices used in utility-scale sector (2.5 MW and above) would fall from 1.22 €/W in 2012 to 0.92 €/W in 2022, [5]. Module prices cost, are contineously deccreasing as shown in Fig. 3b. A list of the countries having the highest PVPS capacity is given in Table 1, [4].

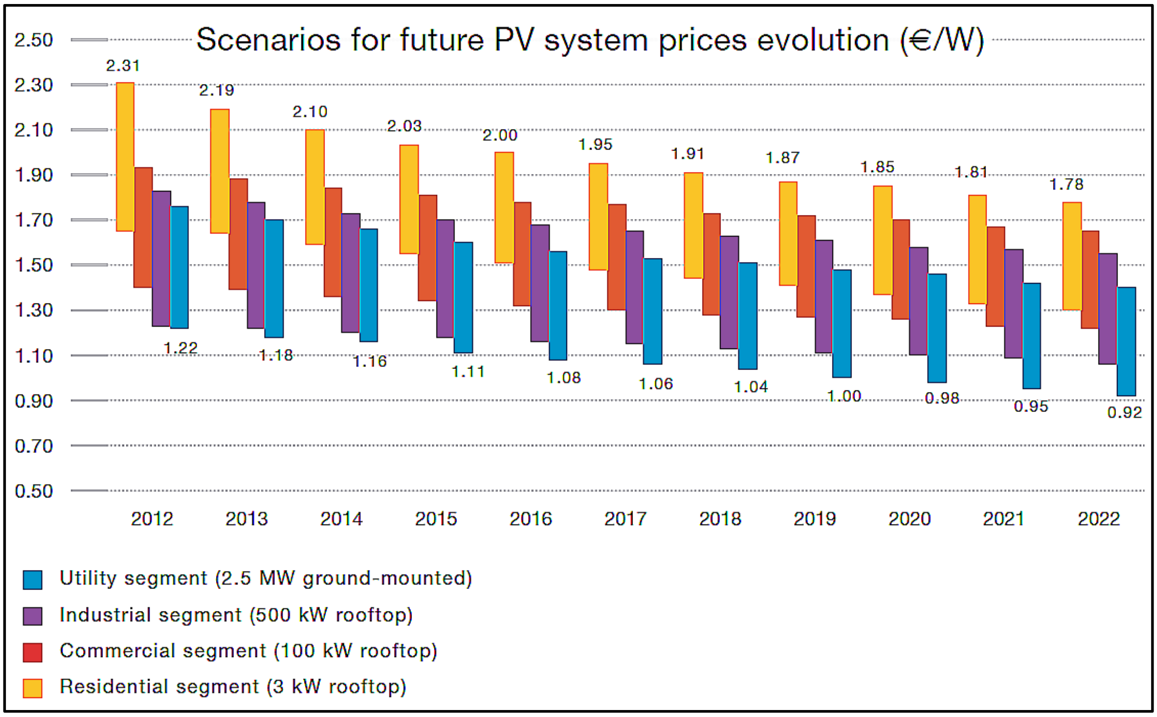

Figure 2a : Future PV Systems Evolution in Euro/W, [2]

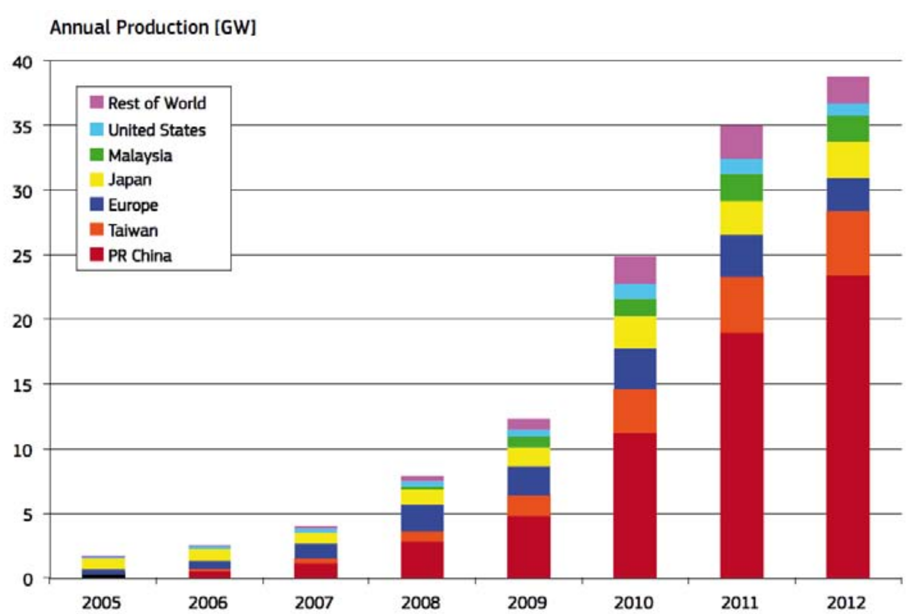

Figure 2b : World PV Cell/Module Production from 2005 to 2012 (data source: Photon International [Pho 2012], PV Activities in Japan [Pva 2013], PV News [Pvn 2013] and own analysis), [3]

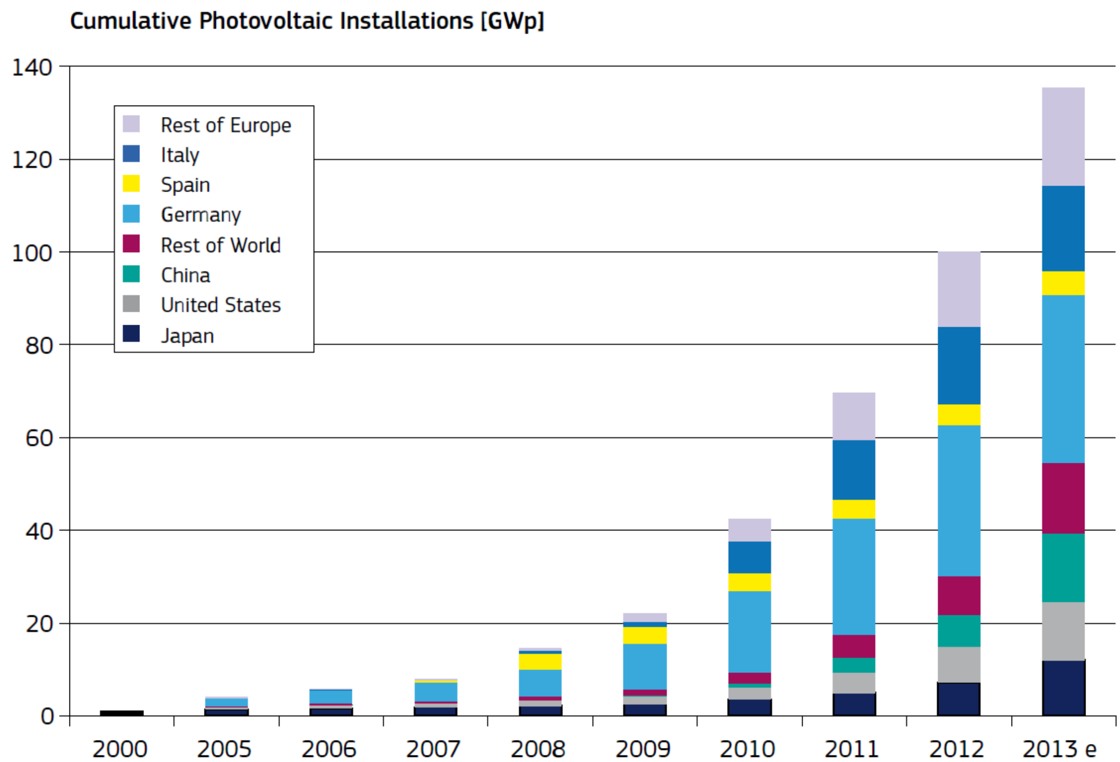

Figure 3a : Cumulative PV Cumulative Photovoltaic Installations [GWp] installations from 2000 to 2013, [3]

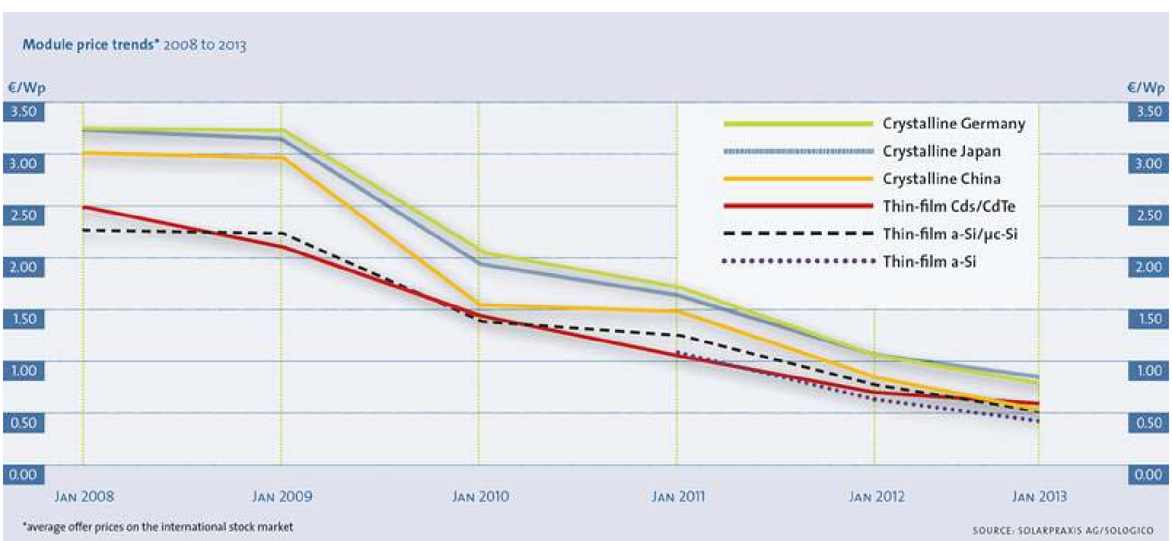

Figure 3b : Module price trends, [4]

Table 1 : Top 15 markets 2012 worldwide, [5]

	Country	2012 Newly Connected Capacity (MW)	2012 Cumulative Installed Capacity (MW)
1	Germany	7,604	32,411
2	China	5,000	8,300
3	Italy	3,438	16,361
4	USA	3,346	7,777
5	Japan	2,000	6,914
6	France	1,079	4,003
7	Australia	1,000	2,412
8	India	980	1,205
9	United Kingdom	952	1,829
10	Greece	912	1,536
11	Bulgaria	767	908
12	Belgium	599	2,650
13	Spain	276	5,166
14	Canada	268	765
15	Ukraine	182	373
	Rest of the World	2,692	9,546
	Total	31,095	102,156

In Qatar, the advantages of using PVPS are clear. The primary solar energy (sunlight) is free and abundant, no moving parts and thus the needed maintenance is low, and low operating cost as no fuel is used. No water is required for operation except that needed for cleaning the panels. The decreasing cost of the PV modules lowers the capital cost and drives for installing more PVPS. The main factors hindering the spread of PVPS are still high capital cost, large needed site area, and the fact that the PVPS are not dispatch-able plants. The site area of a PVPS having 15% efficiency and fixed tilt modules is about 10,000 m^2/MW in tropic regions (23.5 degrees to the North and South of the Equator respectively); and up to 20,000 m^2/MW in Northern Europe. One square kilometer site can be used for 50 MW. This area increased about 10% for a single axis tracker, and 20% for a 2-axis tracker to avoid shadow.

The largest cost of PVPS is still that for the modules, (accounts for about 50% of total cost), followed by costs of installation materials, labor, and the inverters. The inverters replacement cost can be significant. The PV modules warranty is generally about 20–25 years long; while, the inverters warranty is typically 10–15 years long. Improvements are rapidly achieved in many subsectors, [6].

Ratings of PVPS are usually given in terms of the solar arrays DC peak capacity in MWP, or nominal maximum AC output in MW or mega volt-amperes (MVA). Solar parks usually have medium capacity (1-20 MW), although there are large capacity operating PVPS in operation, and large plants capacity (up to one GW) are planned. The Agua Caliente solar project is now the largest operating PVPS with 290 MW in Yuma County, Arizona. Figure 5 shows a 3.5 MW plant operating in Saudi Arabia.

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Figure 5 : Saudi Arabia: The ground-mounted photovoltaic plant with a peak output of 3.5 MW is located in Riyadh in the grounds of the KAPSARC (King Abdullah Petroleum Studies and Research Center), the largest oil research center in the world, Photo: Phoenix Solar AG, [4]

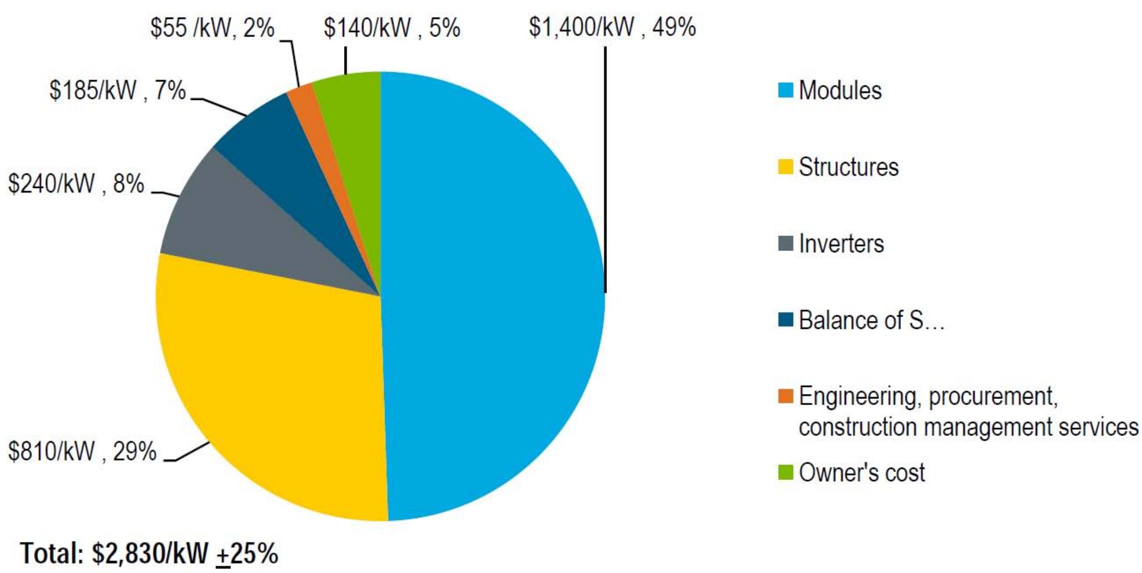

Figure 6a : Utility-scale PV facility by cost component, [7]

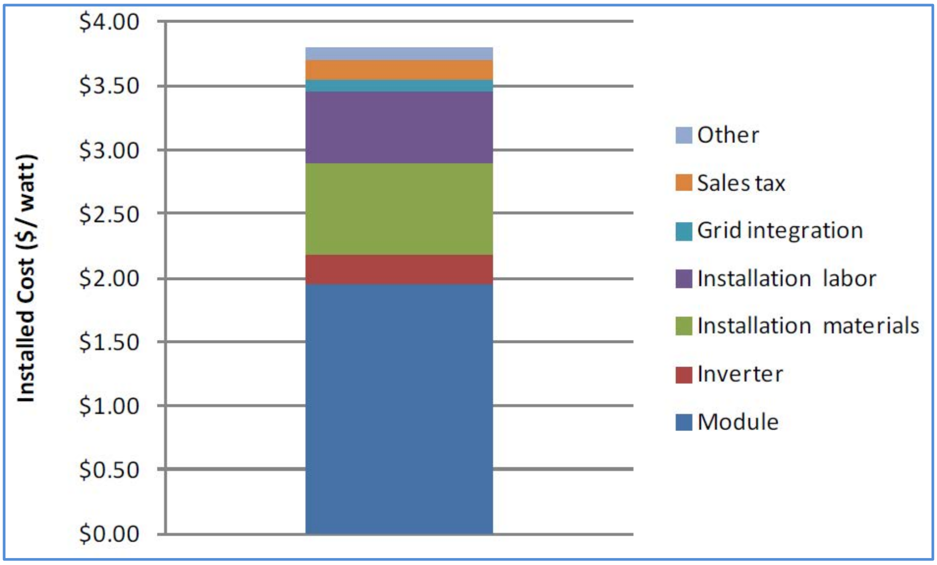

Figure 6b : Utility-scale PV facility by cost component, 2011, [7]

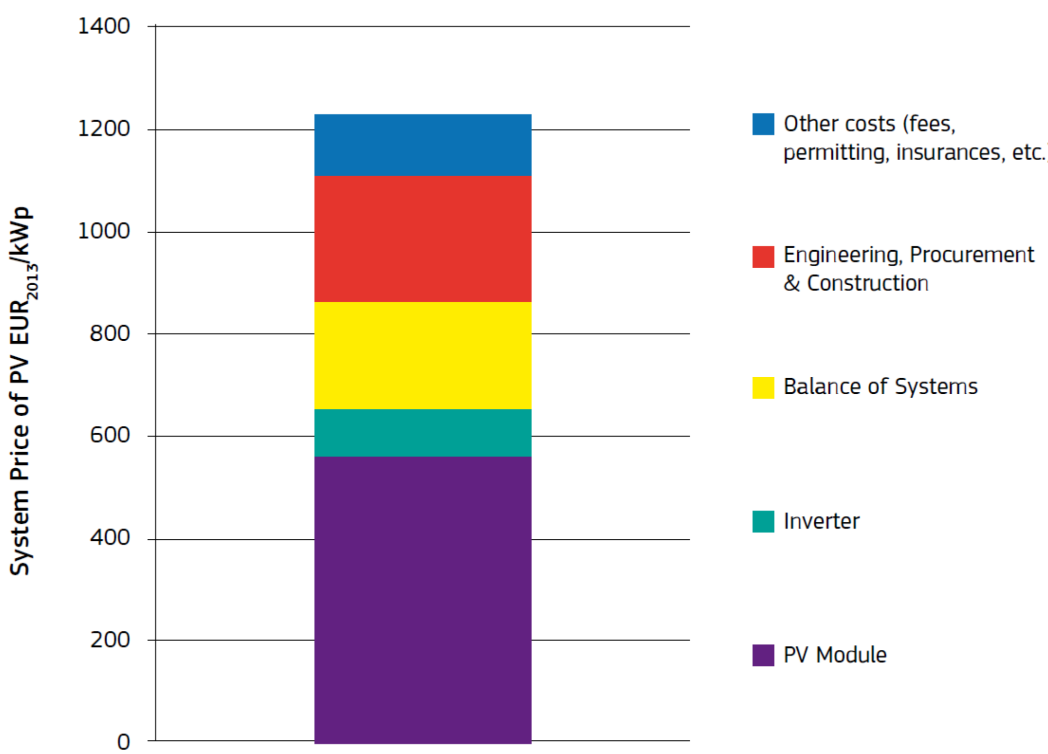

Figure 6c : Utility-scale PV facility by cost component, 2013, [3]

The cost breakdown for a fixed-tilt utility-scale PV system utilizing crystalline-silicon (c-Si) modules is shown in Figs. 6a-6c. Lower efficiency thin-film modules generally cost less but can have higher balance of plant (or non-module) expenses. This includes costs for supporting structures, DC cabling, and inverters.

The PVPS high cost and low load factorin comparison with conventional EP generation plants options are the main obstacles against the widespread of the PVPS. Factors that can improve the competitiveness of PVPS with other EP generating systems are:(a) cost reductions of solar cell modules, (b) growing concerns about energy security and climate change, and (c) continuous increase of the fossil fuels cost. Solar panel cost per watt have been falling steadily from $70/W in 1970 to $4/W in 2011, (this cost does not reflect the total system cost, which will vary widely based on the application.). However, the PVPS cost is still expensive compared to other power generation systems, [8]. The cost of the Gas Turbine Combined Cycle (GTCC) power plants that are commonly used in Qatar is low, in the range of $1.5/W compared with $5/W for the PVPS.

The National Renewable Energy Laboratory (NREL) in US, [9], conducted an analysis showed that the 2010 prices of PV systems in the US (cash purchase, before subsidy and considering reported target installer operating overhead and profit margins) are:

- $5.71/WP DC – 5 kWP DC residential rooftop
- $4.59/WP DC – 217 kWP DC commercial rooftop
- $3.80/WP DC – 187.5 MWP DC fixed-axis utility-scale ground mount
- $4.40/WP DC – 187.5 MWP DC one-axis utility-scale ground mount

The US showed great growth in solar power plants. Solar parks capable of delivering a total capacity of up to 750 MW are being planned or are already under construction in California, Arizona, New Mexico and Nevada.

In the hot summer in the GCC, the highest demands of EP occur in the afternoon when air conditioning machines in homes and public building are working at their highest capacity and solar power produces its maximum yields.

II. Photovoltaic (pv) Power Plant Systemcomponent

The structure of a PV cell, as shown in Fig. 7a, has two semiconductor materials, the n-type that has extra electrons in a conduction band, and the p-type that has extra holes in a valence band. When photons of greater energy than the semiconductor band gap energy, Eg, see Fig. 7b, are absorbed by the cell, the photons excite the electrons of the composite material into a higher state of energy. This allows the electrons separation from their atoms, drive electrons from the valence band to the conduction band. The movement of electrons is allowed in single direction by the nature of solar cell composition. Due to the electrons separation, positive charges are created (called holes) that flow in direction opposite of the released electrons, and this creates holes-electron pairs flowing in opposite directions across the junction, and act as charge carriers for a direct electric current. This process is called photovoltaic (PV) effect. The generated electron/hole pairs by the energy of the incident photons overcoming the energy band gap of the PV material to make a current flow according to the built-in potential slope, typically with a p-n junction of semiconductor, in the material. The freed electrons carried away by metal electrodes, and power is produced by connecting the electrodes to an external load. So, the operation of solar cells is based on the binding energy of electrons of a crystal. Two bands, called conduction and valence, can be totally or partially occupied by electrons, Fig. 7b. Therefore, the PV cells consist of layered of semiconductors in contact with metal electrodes and covered by a protective transparent glazing. The semiconductor material used in cells is predominantly silicon because the band gap energy of silicon results in theoretical efficiency very near to the maximum for solar radiation. The maximum efficiency of a PV cell can be increased further if multiple semiconductor layers, or junctions, are stacked. In this case, the band gap of each layer is optimized for a different range of photon energies, thereby taking advantage of a greater range of the solar spectrum and improving the overall cell efficiency. A solar module consists of assembled and connected solar cells, and an array consists of assembled and connected solar modules. The array converts solar energy into a usable amount of direct current (DC) electricity.

a) Main Components

The main components in the PV power systems include:

i. *Solar PV modules*

As given before, a PV module is combination of PV cells that produce direct electric current (DC) from sunlight with no moving parts.

Typical cells of 3W, 0.5 volts can be connected in series to produce summation of the 0.5 volts and power. When cell are connected in parallel, the output current will be the summation of current produced by the cells, but the voltage would be that of the cell.

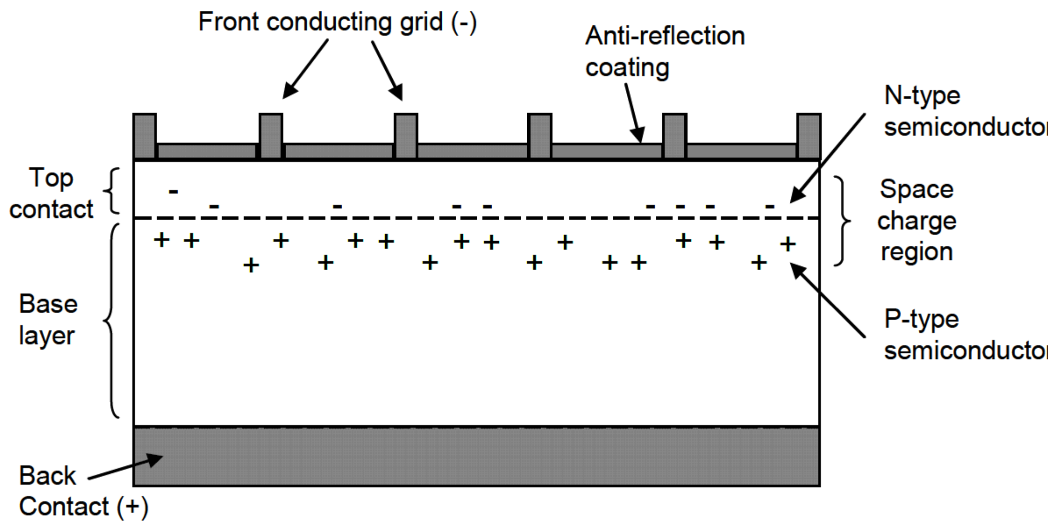

Figure 7a : PV cell structure, [10]

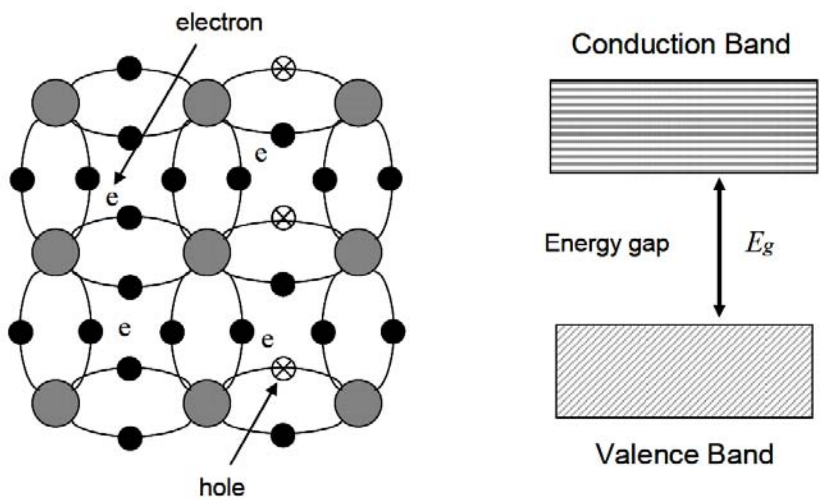

Figure 7b : The cells are electrically connected in series and in parallel to form a module, [10]

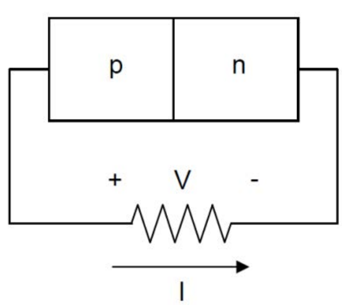

Figure 7c : Operating scheme of photovoltaic cell, [10]

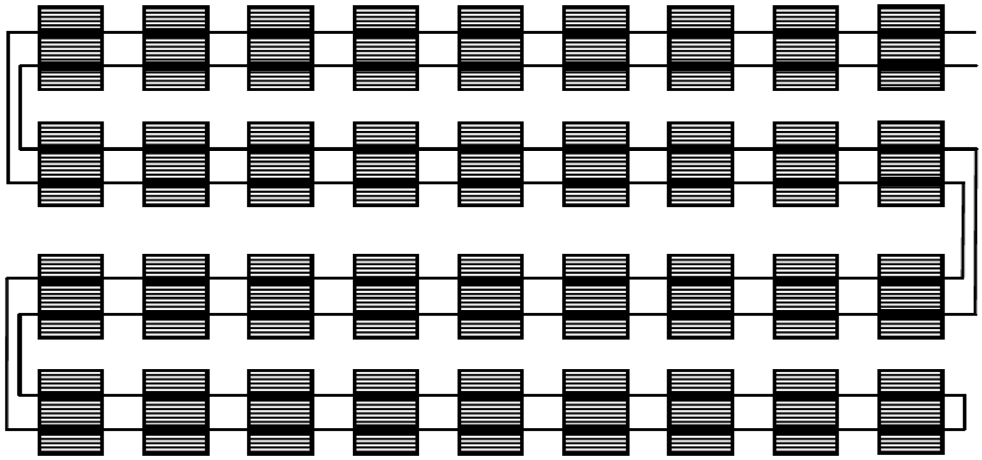

Figure 7d : Sturcture of a PV module consisting of 36 cells connected in series, [10]

When modules are connecting in series, high voltage can be obtained; and when connected in parallel, high current can be obtained.

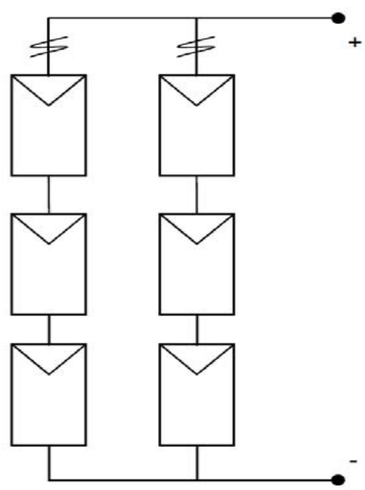

Figure 7e : Modules forming a panel connected in series-parallel with internal by pass diodes and series fuses, [10]

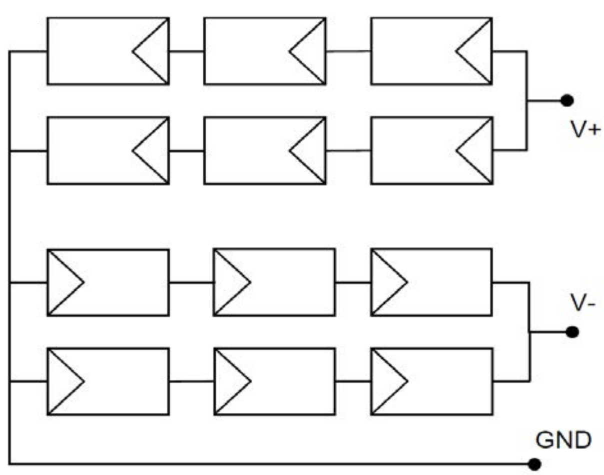

Figure 7f : Modules forming a panel connected in series-parallel with center grounded to provide + and – supplies (fuses and diodes not shown), [10]

Figure 8a shows the current (I)-voltage (V) for a module at specific irradiance. It shows the short circuit current (I_{sc}), open-circuit voltage (V_{oc}) and the maximum power point (Imp; V_{mP}), at which maximum power is attained. These three points are usually given by the PV cell manufacturers as shown for a typical PV module (KC200GT).

The I-V curves of modules are affected by the irradiance and temperatures as shown in Fig. 8a and 8b, [11].

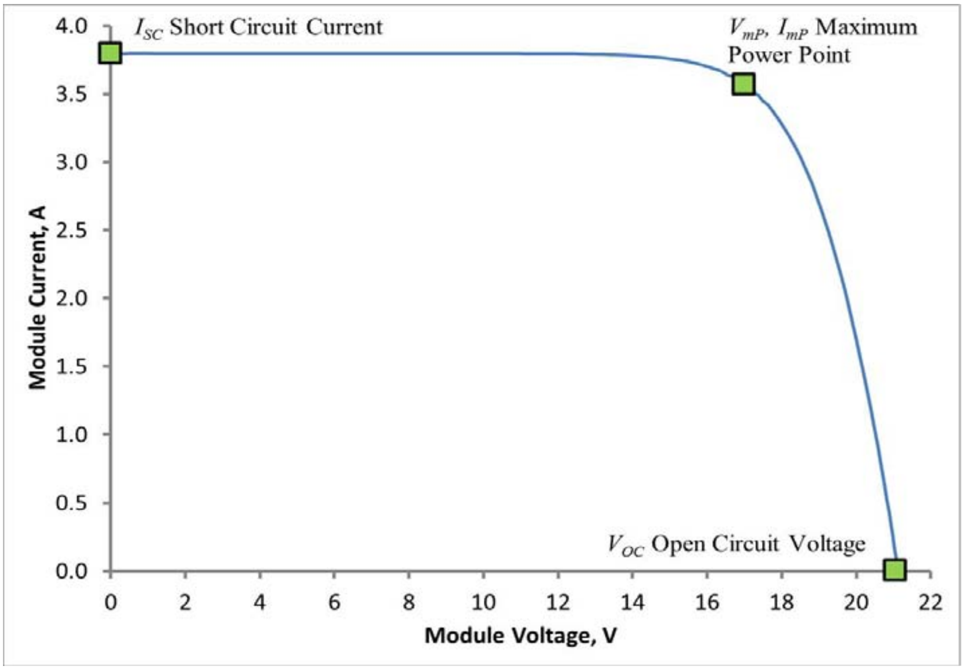

Figure 8a : Photovoltaic module I-V characteristics

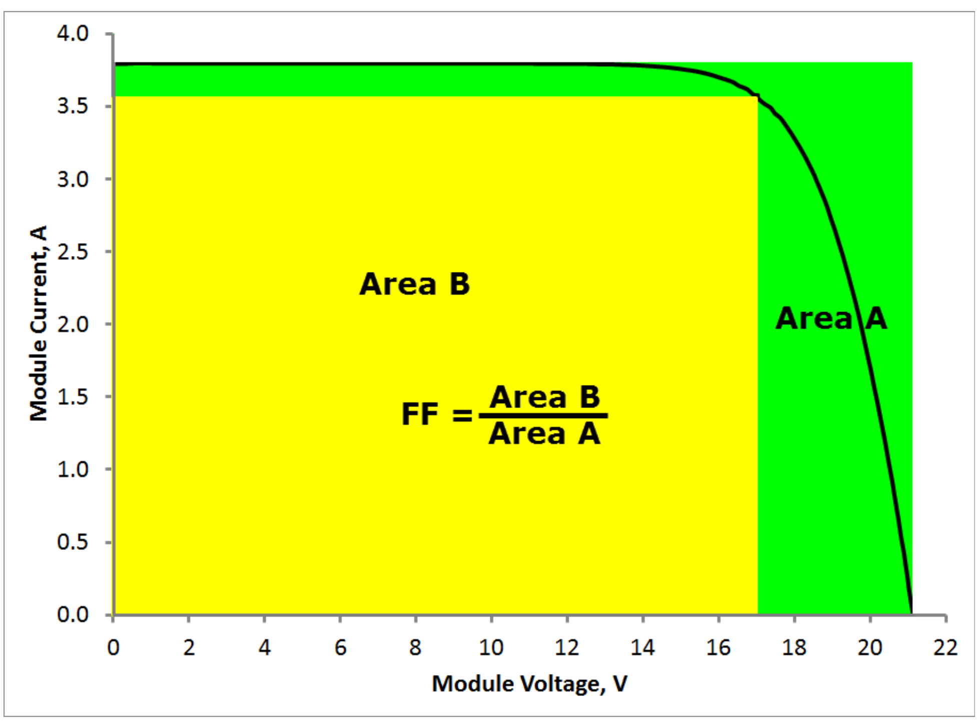

Figure 8b : Photovoltaic module characteristics showing the fill factor, [11]

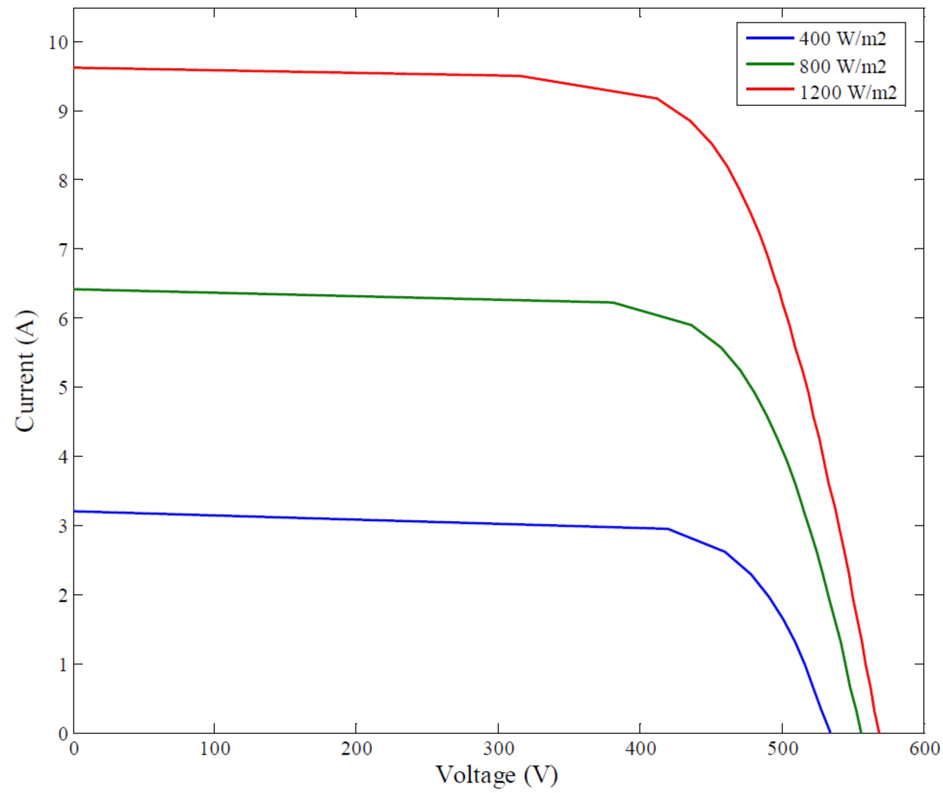

Figure 8c : The effect of irradiance on the I-V characteristics for typical module, [11]

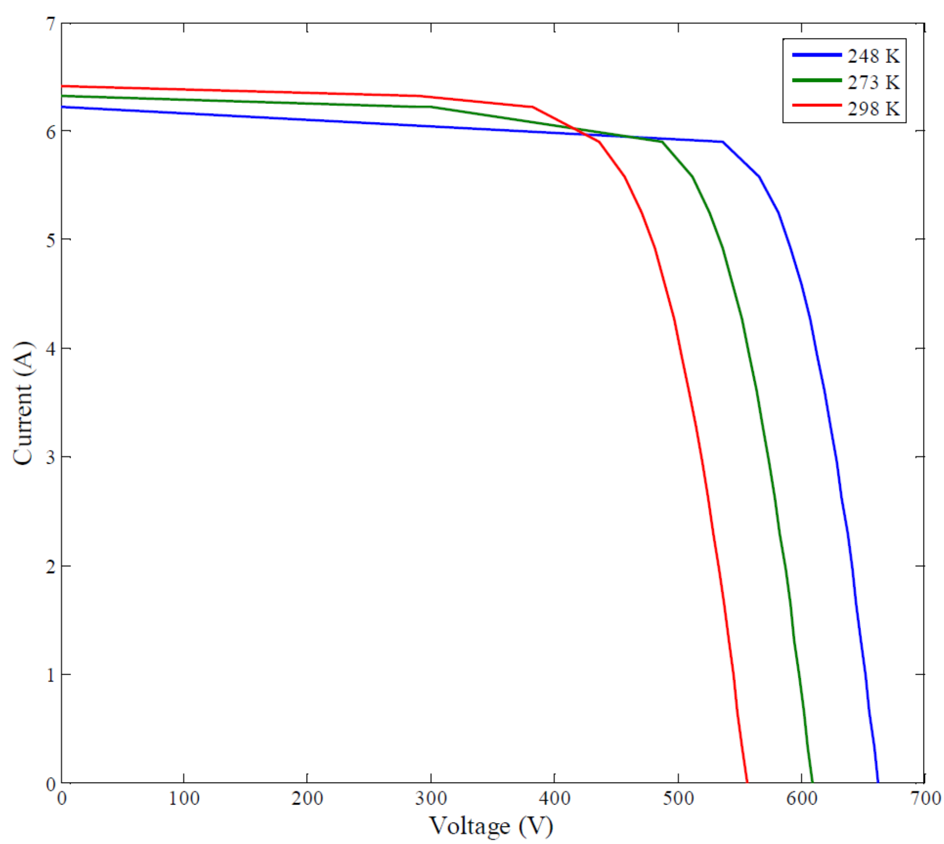

Figure 8d : The effect of temperature on the I-V characteristics for typical module at 800 W/m^2 irradiance, [11]

Table 2 : Datasheet Parameters for KC200GT, [12]

Irradiance	1000 W/m^2	800 W/m^2
Maximum Power Point Current	7.61A	6.13A
Maximum Power Point Voltage	26.3V	23.2 V
Maximum Power Point	200.14 W	142W
Short Circuit Current	8.21 A	6.62 A
Open Circuit Voltage	32.9V	29.9 V

The maximum power point (optimum operating point) shown in Figs 8a and 8b of a PV module is function of cell temperature and in solation level and array voltage, as shown in Fig. 8d for a PV called KC200GT module are given before. A maximum power point tracker (MPPT) is needed to operate the PV array at this optimal point.

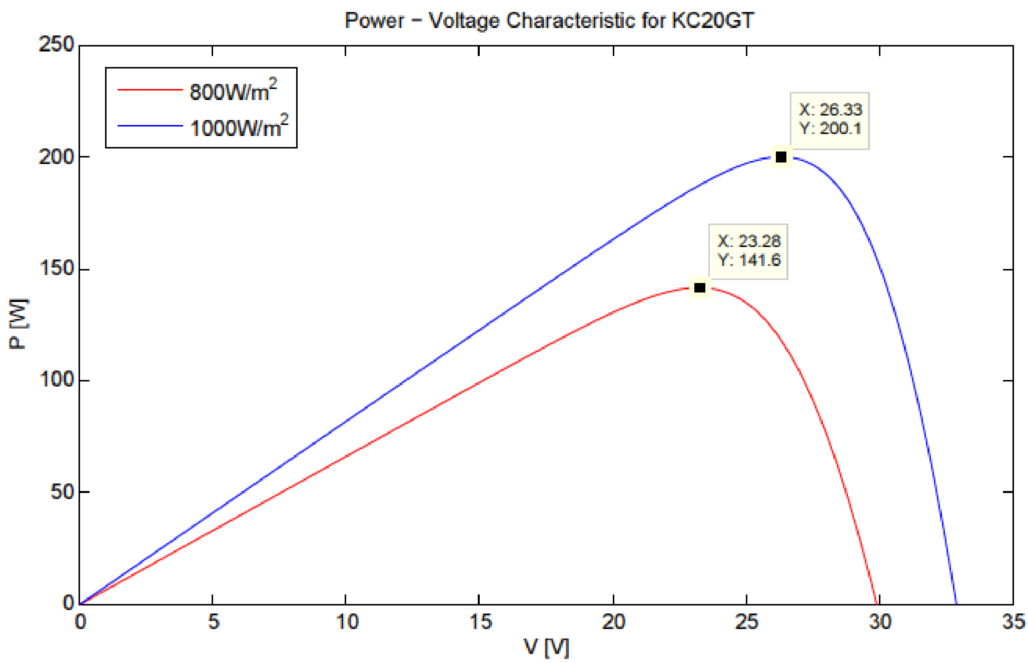

Figure 8e : Power-voltage characteristics of KC200GT, [12]

ii. *Inverters (or converters)*

Inverters convert the generated DC to alternative current (AC) in order to be connected to the utility grid. The modules are connected to the inverters through series strings and parallel strings. The PV systems connected to the grid normally do not have any real influence on the grid voltage. Their voltage operation range are therefore more of a protection function that is used for detecting abnormal utility, rather than regulators

iii. *Step-up transformers*

Further step-up of the inverters voltage output to that required by the AC grid voltage (e.g. 25kV, 33kV, 38kV, 110kV depending on the grid connection point) is conducted by further step-up transformers; see Figure 9, [1].

iv. *Module mounting (or tracking) systems*

The modules should be attached to the ground. They can face the sun at fixed tilt angle, or they can be fixed to frames that track the sun.

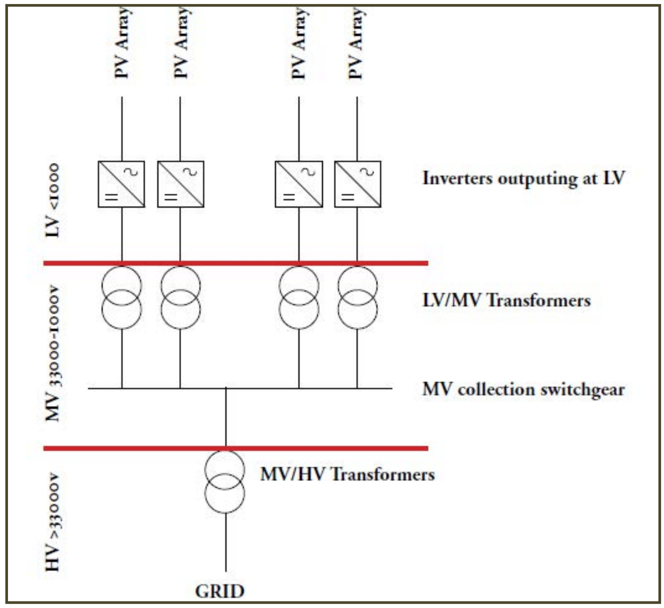

Figure 9 : Typical Transformer Locations and Voltage Levels in a Solar Plant where Export to Grid is at HV, [1]

The substation and metering points are usually located outside the PVPS and typically located on the network operator's property. Connections to the grid network are of major concern when building PVPS in terms of the availability, locality, and capacity. This network should be able to absorb the maximum capacity of the PVSP. The PVPS may be sited at a distance (few kilo-meters) of a suitable grid connection point.

b) Photovoltaic Cell Materials

Most PV cells are manufactured from silicon (Si) that doped with negatively and positively charged semiconductors of phosphorous and boron. When sunlight is received by the PV cell, electrons become free to flow from the negative phosphorus to the positive boron. The produced DC is obtained through a metal grid covering the cell and external circuit. Besides crystalline silicon (c-Si), and amorphous silicon (a-Si) thin-film technologies, only cadmium telluride (CdTe) has had significant success in utility-scale solar development.

Silicon (Si) material can be mono-crystalline, poly-crystalline and amorphous silicon. Ribbon cast polycrystalline cells are also produced by drawing, through ribbons, flat thin films from molten silicon to reduce the silicon waste by sawing from ingots and thus reduces its cost. Other than silicon materials, gallium arsenide (GaAs), cadmium telluride (CdTe), copper indium diselenide (CIS) and copper indium gallium selenide (CIGS) are used in PV cells manufacturing.

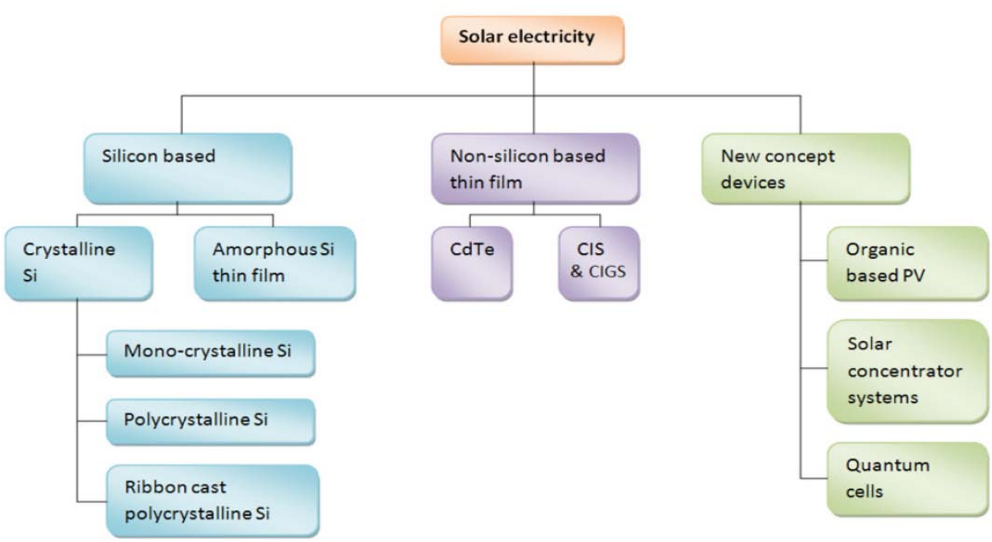

Figure 10a : PV cells material Technology [13]

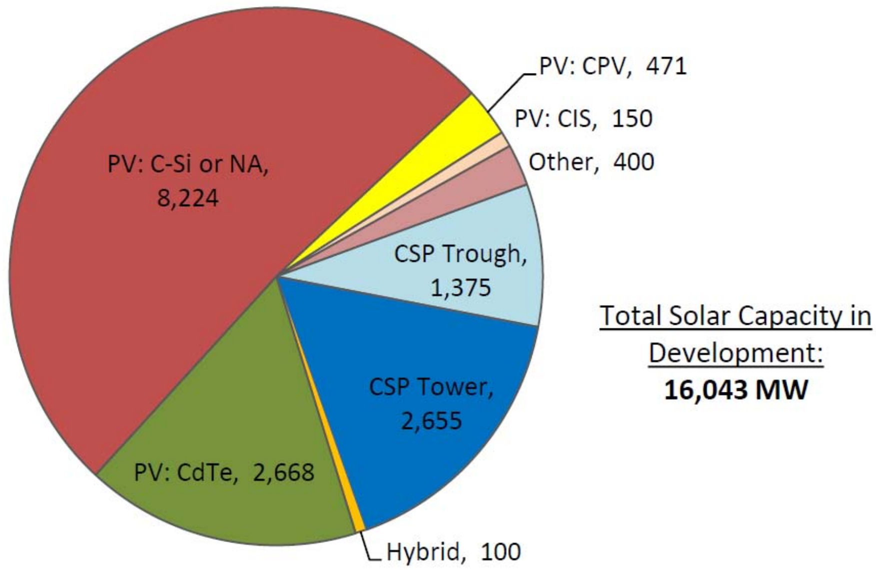

Fig. 10b : Total U.S. utility-scale solar capacity under development (all numbers in MW)

Among the utility scale PV plants in the US, about 24.5% use CdTe, and 74.5% use c-Si, see Fig. 10b.An overview of the different main PV cells materials is given in Fig. 10. The mono-crystalline cells are made of pure silicon, have grey or black color, more efficient (16–24%) than the polycrystalline silicon (14–18%), see Table 3. Solar panel efficiency is the ratio of electric power produced by a PV module to the power of the sunlight striking the module.

The polycrystalline silicon cells are easier to be manufactured (to be sawed from ingots) and thus cheaper but less efficient than the mono-crystalline cells, and have shiny blue color. Amorphous silicon (so called thin-film) cells consist of non-crystallized very thin layers deposited onto a substrate, has brown or red-brown color, reddish brown, and typical efficiency of 4% to 10%, see Table 3.The power per unit area is typically 75–155 Wp/m^2 for mono -crystalline and poly-crystalline modules, and 40–65 Wp/m2 for thin-film modules [13].

The other thin-film cells, other than the amorphous silicon, are Cadmium telluride (CdTe) and Copper indium (gallium) di-selenide (CIGS). The CdTesolar cells are manufactured on as ubstrate glass with transparent conducting oxide (TCO) layer usually made from fluorinated tin oxide (FTO) as the front contact. This is initially coated with an n-type cadmium sulfide (CdS) window layer and secondary with the p-type CdTe absorber layer. The color is reflective dark green toblack and typical cell efficiencies are 9.4–13.8%. The conversion efficiencies of Copper indium selenide (CIS), and Copper indium (gallium) di-selenide (CIGS) cells are shown in Fig. 10b. Values for the highest reported efficiencies of CdTe and CIGS solar cells are shown in Fig. 10b.

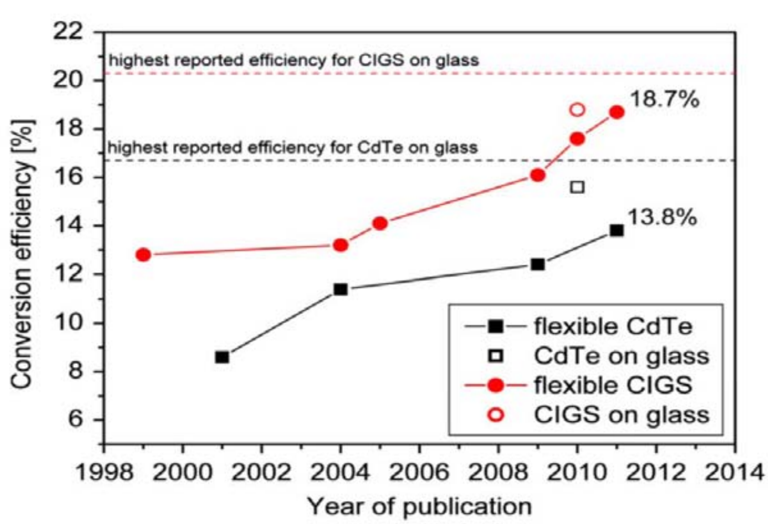

Figure 10c : Conversion efficiencies of flexible CdTe and CIGS solar cells fabricated by low temperature processes Also shown is the in-house reference on glass and the highest reported efficiency for each technology, [13] The silicon-based crystalline (c-Si) wafers usually give high solar cells efficiency but at high manufacturing cost. The thin film cells are cheaper but less efficient, [1].

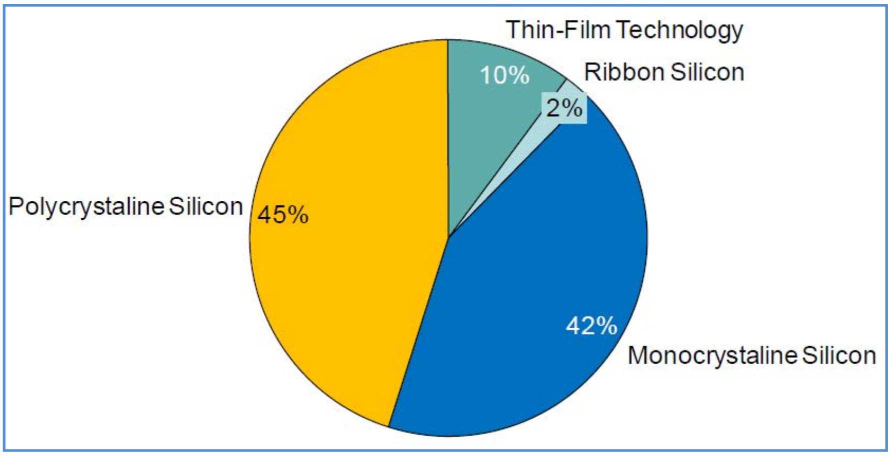

Figure 10d : Market share with regard to technology [in percent], [14]

The characteristics of the cell material affect the cell performance, cost, and methods of manufacture, [3].

In 2010, 78% of the cells used PVPS were wafer-based crystalline silicon modules; and the percentage of amorphous silicon and cadmium telluride thin film modules was 22%. The solar cell materials are classified in Figure 7, [1], and their main characteristics are given in Table 3, [1].

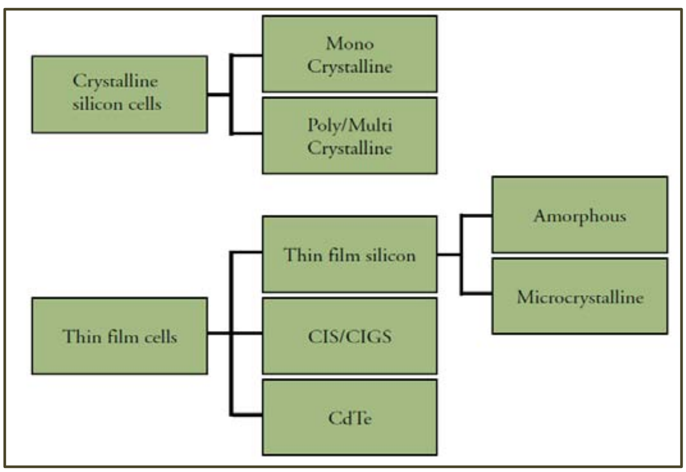

Figure 10b : PV Technology material classes, [1]

Table 3 : Characteristics of various PV technologies, [1]

Technology	Crystalline Silicon	Amorphous Silicon	Cadmium Telluride	Copper Indium Gallium Di-Selenide
Abbreviation	c-Si	a-Si	CdTe	CIGS or CIS
Cost ($/Wp, 2009)	3.1-3.6	2.5-2.8	2.1-2.8	2.7-2.9
Percentage of Global installed capacity	78%	22%		
Thickness of cell	Thick layers (200-300 µm)	Thin layers (<1 µm)	Thin layers (<1 µm)	Thin layers (<1 µm)
Current commercial efficiency	12-19%	5-7%	8-11%	8-11%
Temperature coefficient for power (typical)	-0.5%/°C	-0.21%/°C	-0.25%/°C	-0.36%/°C

Table 3 shows that the cell efficiencies are in the range of 5-7% for amorphous, and 12-19% for the thick layers c-Si. The efficiency can reach up to 44.0% with multiple-junction concentrated photovoltaic, [3].

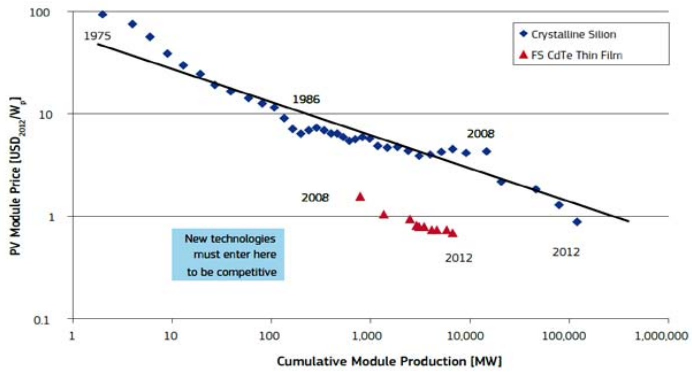

Fig. 10e : Price-experience curve for solar modules (data source: Bloomberg New Energy Finance and PV News), [3]

c) PV Degradation

The performance of PV modules is degraded over time. High degradation occurs in the first year upon initial exposure to light and then it stabilizes. Degradation is mainly affected by used module characteristics. Irreversible light-induced degradation is suffered by c-Si modules due to the presence of boron, oxygen or other chemicals left after cells production. The so called Staebler-Wronski Effect, [15], degrades the amorphous silicon cells, and can cause 10-30% power output reductions in the first six months of exposure to light before stabilization with much less degradation rates. The performance of amorphous silicon cells after stabilization is usually given by the manufacturers. The performance of amorphous silicon is affected by temperature. The modules perform better in hot summer, and drop in cold winter.

Degradation can be caused also by environment effects such as air pollution, dis-coloring or haze of the lamination defects, humidity, and wiring degradation. Degradation can be reduced by regular maintenance and cleaning.

In general, long term of power output degradation rate ranges between 0.3 and 1% per year. Banks often assume a flat rate of degradation rate of 0.5% per annum, [15].In general, good quality PV modules may be expected to have a useful life of 25-30 years.

III. Pv System Performance

a) PV Cell and Module Ratings

The solar modules are compared with each other based on standard test conditions at normal irradiance rate of 1000 W/m^2, cell temperature 25°C and Air Mass (AM)=1.5. The AM is corresponding of receiving surface at 37° tilt angle towards the equator facing the sun.

Solar insolation is the integration of irradiance over a specified time, usually day, year or an hour. Therefore, the insolation has a unit of Watt-hours per square meter. The insolation is usually denoted by *H* is used for insolation for one day; *I* is used for insolation for an hour or year. The symbols *H* and *I* can represent beam, diffuse or global and can be on surfaces of any orientation. Solar radiation consists of beam (direct) radiation received from the sun without having been scattered by the atmosphere, and diffuse radiation received from the sun after its direction has been changed by scattering in the atmosphere. The sum of the beam and the diffuse solar radiation on a surface, global radiation, is often referred to as total solar radiation. The most common measurements of solar radiation are global radiation on a horizontal surface, referred to as global horizontal radiation.

Peak sun hour is the total number of hours of a day that can receive radiation; it is an equivalent form of insolation and most radiation data is represented using either of these units expressed as kWh/m^2/day. The figure below shows the annual insolation map of the United States.

The performance ratio (PR) of the PVPS is defined as percentage ratio of the AC yield to the installed capacity in kWp multiplied by plane array irradiation in kWh/m^2,[1]. It gives the yield to the maximum nominal output. The PR does not take in consideration the size or the solar resource. A PVPS of high PR converts solar energy to electric power efficiently, and can be achieved by well-designed solar PVPS and not operated in high temperature conditions. The PR of varies between 77% in summer to 82% in winter. Amorphous silicon modules in some PVPS show the opposite effect with high PR in hot summer and low PR in cold winter. Electrical losses decrease the PR, [10], see Table2.

Throughout the components of the system there are electrical losses, which de-rate the conversion from nameplate DC power rating to AC power rating (as explained in Table 4), [16]. Table 4 gives the losses due to the several system components.

Table 4 : De-rate the conversion from nameplate DC power rating to AC power, [16]

Derate Factors for Photovoltaic System Components Table 6. PVWatts Default Derate Values		
Component Derate Factors	PVWatts Default	Range
PV module nameplate DC rating	95%	0.80–1.05
Inverter and transformer	92%	0.88–0.98
Mismatch	98%	0.97–0.995
Diodes and connections	100%	0.99–0.997
DC wiring	98%	0.97–0.99
AC wiring	99%	0.98–0.993
Soiling	95%	0.30–0.995
System availability	98%	0.00–0.995
Shading	100%	0.00–1.00
Sun-tracking	100%	0.95–1.00
Age	100%	0.70–1.00
Overall DC-to-AC derate factor	77%	0.09999–0.96001

Table 4 notes that the overall DC-to-AC de-rate factor varies for different PV systems and applications. NREL's PVWatts tool incorporates a standard de-rate factor of 0.77 (or a 23% loss in output from nameplate DC rating to actual AC energy produced).

The load (or capacity) factor of a PVPS power plant (usually expressed in percentage) is the ratio of the actual output over a period of one year and the target yield (output if it had operated at nominal power the entire year), and is defined as:

$$\text{CF} = \frac{Actual\ yield\ E}{Target\ yield} = \frac{Annual\ Energy\ Generated(kWh)}{8760(hours/\ annum) \times Installed\ Capacity(kWp)}$$

Note that the target yield (dominator) is different from the annual sum of global irradiation, h, that hits the module, and it depends on the specific location. The value of h is to be obtained from measurements, or from an irradiance map, and its units is kWh/m^2. The relation between the target a_{out} and h is given by: $\text{Target yield} = h A \eta_{norm}$

This gives $\frac{Actual\ yield\ E}{Target\ yield} = \frac{E}{h A \eta_{norm}} = \eta_{pre} \eta_{rel}\, \eta_{sys}$

Where, η_{nom} = Nominal efficiency

η_{pre} = Conversion efficiency

η_{rel} = Relative efficiency

η_{sys} = system efficiency

The performance ratio is independent from the irradiation *h* and therefore it is useful to be used to compare systems. The specific final yield, Y_f, (kWh/kWp) is the total annual energygenerated E in kWh divided by the nameplate DC power P0 of the installed modules capacity (kWp), i.e., Y_f =E/Po. Another useful expression is the specific yield to the standard conditions of 1 kW/m^2 irradiance Y_r. The reference yield Y_r is the total in-plane irradiance H divided by the PV's reference irradiance G, i.e., Y_r = H/G (hours). Therefore, Y_r is the number of peak sun-hours or the solar radiation in units of kWh/m^2. The performance ratio PR is the Y_f divided by the Y_r, i.e., PR= Y_f/Y_r (dimensionless).

Qatar annual global horizontal irradiation GHI are given as: 2055 kWh/m^2 (minimum), 2160 kWh/m^2 (maximum), 105 kWh/m^2 (range) and 2134 kWh/m^2 (mean), [17]. The fixed tilt PVPS capacity factor plant in sunny areas is about 16%. This means that a PVPS of 100 MWp plant would generate the equivalent energy of 17.7 MW by combined cycle (CC) having 90% CF.

b) Photovoltaic Power Station

The largest solar PVPS as of March 2014 are given in Table 5.

Table 5 : Large-Scale Photovoltaic Power Plants, Ranking 1-50, [18]

Power	Location	Description	Commissioned
320 MWp	Longyangxia Dam, Qinghai Province ,China,	Longyangxia Hydro-solar PV Station	2013
250 MW	san Luis Obispo, CA, USA	California Valley Solar Ranch	2012-2013
250 MW	Yuma County, AZ, USA	Agua Caliente Solar Project	2012
214 MW	Charanka, India	PV power plant	2012
200 MWp	Gonghe County, Qinghai Province, China	Charanka Park, Patan district, PV power plant	2012
200 MWp	Golmud, China	Golmud PV power plant	2011
166 MWp	Meuro, Germany	SolarparkMeuro	2011-2012
150 MW	Sonoran desert, AZ, USA	Mesquite Solar I	2011-2012
145 MWp	Neuhardenberg, Germany	SolarparkNeuhardenberg	2012
143.2 MW	Kern County, CA, USA	Catelina Solar Project	2013
139 MW	El Centro, Imperial Valley, CA, USA	Campo Verde Solar Project	2013
128 MWp	Templin, Germany	Solarpark Templin	2012
125 MW	Maricopa County, AZ, USA	Arlington Valley Solar Energy II	2013
115 MWp	Toul-Rosières, France	Centralesolaire de Toul-Rosières	2012
105.56 MWp	Perovo, Ukrane	Perovo I-V PV power plant	2012
100 MW	Chengde, Hebei Province, China	Chengde PV Project Phase I and II	2013
100MW	Jiayuguan, Gansu Province, China	Jiayuguan PV power plant	2013
100 MW	Xitieshan China	Xitieshan I,II,III PV power plant	2012
97 MW	Sarnia, Canada	Sarnia PV power plant [2]	2009-2010
92 MW	Boulder City, NV, USA	Copper Mountain II Solar Facility	2012
91 MW	Briest, Germany	SolarparkBriest	2011
84.7 MWp	Finowfurth, Germany	SolarparkFinowTower I,II	2010-2011
84.2 MWp	Montalto di Castro, Italy	Montalto di Castro PV power plant	2009-2010
84 MW	Lopburi, Thailand	Lopburi PV power plant	2011-2012
82.65 MWp	Ohotnikovo, Ukraine	Ohotnikovo PV power plant	2011
82 MWp	Senftenberg, Germany	SolarparkFinsterwalde I,II,III	2009-2010
80.245 MWp	Finsterwalde, Germany	SolarparkFinsterwalde I,II,III	2009-2010
80 MWp	Eggebek, Germany	SolarparkEggebek	2011
75 MWp	Kalkbult, Northern Cape, South Africa	Kalkbult PV facility	2013
71 MWp	Turnow-Preilack, Germany	SolarparkLieberose	2009-2011
70.556 MW	San Bellino, Italy	San Bellino PV power plant	2010
70 MW	Kagoshima pref., Japan	Kagoshima Nanatsujima Mega Solar Power Plant	2013
70 MW	Wittstock, Germany	Solarpark Alt Daber	2011
69.7 MWp	Crimea, Ukraine	Nikolayevka Solar Park	2013
68 MWp	Sault Ste.Marie, Canada	Starwood SSM I,II,III	2010-2011
67.2 MWp	Losse, France	ParcSolaireGabardan	2009-2011

66 MW	Los Angeles, USA	Alpine Generating Station	2013
60.4 MWp	Karadzhalovo, Bulgaria	Karadzhalovo Solar Park	2012
60 MWp	Crucey, France	Centralesolaire de Crucey	2012
60 MWp	Olmedilla de Alarcon, Spain	Parque solar Olmedilla de Alarcon	2008
58 MW	Boulder City, NV, USA	Copper Mountain I Solar Facility	2010
56 MW	Massangis, France	ParcSolaireMassangis	2012
55 MW	Rajastan, India	PV power plant in Rajastan	2013
54.8 MWp	Priozernaya, Ukraine	Priozernaya Solar Park	2013
54 MWp	Straßkirchen, Germany	SolarparkStraßkirchen	2009
52.284 MWp	Walddrenah , Germany	SolarparkWalddrenah	2012
52 MWp	Brandis , Germany	SolarparkWaldpolenz	2007-2008
52 MWp	Tutow, Germany	SolarparkTutow I,II,III	2009-2011
50 MWp	Weidi, China	Weidi Solar Park	2012
50 MW	Alpaugh, CA, USA	SPS Alpaugh solar project	2012

Notes: Power is specified in MWp if DC array power is known. If DC array power is unknown then output power is specified. In some cases, it is unclear if the power is the output or DC array power. Sarnia power plant has AC power of 80 MW. This power was also disclosed in press release. DC array peak power (97 MWp) is unofficial information and is based on personal communication. SolarparkSenftenberg I (18 MWp) was put into service in 2010 and constructed by Phoenix Solar and is a separated project not related to Senftenberg II and III. Last modified: 3/15/2014.

The PVPS can be divided based on its capacity, to mid-capacity station of less than50 MW, and large capacity plants of 50 MW or more. A NREL report issued in 2012 accounted for 56 PVPS of mid-size ranging from 5- 48 MW each, and total capacity 589.5 MW. There are another 57 PVPS in advance development under development of 20-50 totaling 1,329.5 MW.Concerning large capacity PVPS (greater than 50 MW) in US, there are currently 40 plants of 9,425 MW total capacities in the development stages.

V. Power Conversion

Inverters are required to convert the DC power produced by the modules into AC, which can then be connected to the electrical grid. DC rating to actual AC energy produced. Inverters are solid-state electronic devices. Inverters can also perform a variety of functions to maximize the output of the plant. These range from optimizing the voltage across the strings and monitoring string performance to logging data, and providing protection and isolation in case of irregularities in the grid or with the PV modules.

Technological improvements are rapidly occurring in many subsectors. For example, micro-inverters can be paired with each PV module, in contrast to centralized inverters, which are paired with a bank of modules. Therefore, if a single micro-inverter fails, only the module paired to the failed inverter is affected, [6]

There are two primary alternatives for configuring this conversion equipment; centralized inverter and string inverter, see Figure 11.

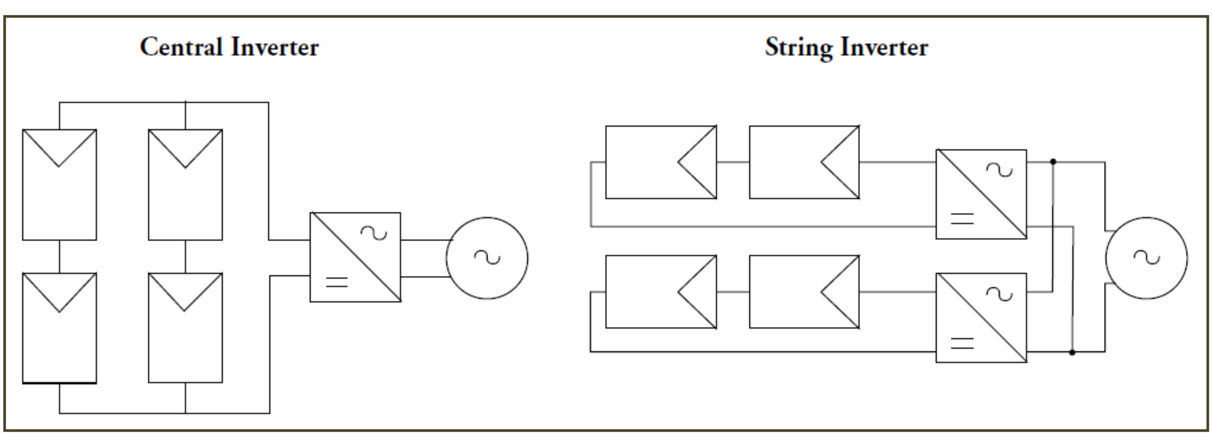

Figure 11 : PV System Configurations, [1]

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In central inverters,large numbers of modules are connected in series to form a high voltage string. Strings are then connected in parallel to the inverter, Figure 8. Central inverter configuration is the first choice for many medium and large-scale solar PV plants. Central inverters offer high reliability and simplicity of installation. However, their disadvantages are: increased mismatch losses and absence of maximum power point tracking for each string. This may cause problems for arrays that have multiple tilt and orientation angles, suffer from shading, or use different module types.

Central inverters are usually three-phase and can include grid frequency transformers.

Figure 12 : First Solar 40-MW CdTe PV Array installed by JUWI Group in Waldpolenz, Germany, [19]

The transformer's location in the Waldpolenz Solar Park, shown in Figure 12 is divided into blocks each with a centralized inverter.

String inverters are substantially lower in capacity, of the order of 10kW, and condition the output of a single array string. This is normally a whole, or part of, a row of solar arrays within the overall plant. String inverters can enhance the efficiency of solar parks, where different parts of the array are experiencing different levels of insolation, for example where arranged at different orientations, or closely packed to minimize site area. While numerous string inverters are required for a large plant, individual inverters are smaller and more easily maintained than a central inverter.

VI. Ground Mounting

PV modules must be mounted on a structure to keep them correctly oriented and provides them with structural support and protection. The mounting structures may be either fixed or tracking. The fixed tilt mounting system is simpler, cheaper and has lower maintenance compared to than tracking systems. The tracking systems are more expensive and more complex, but can be cost-effective in locations with a high proportion of direct irradiation.

Most solar parks use ground mounted (sometimes called free-field or stand-alone) arrays. Land area required for solar parks varies depending on the location, and on the solar modules' efficiency, the slope of the site and the type of mounting used. Fixed tilt solar arrays using typical modules of about 15% efficiency on horizontal sites, need about 10,000 m^2/MW.

a) Fixed Tilt

The solar panels in many PV stations are mounted on fixed structures, and thus have fixed inclination calculated to provide the optimum annual output profile, and is generally optimized for each PV power plant according to its location. This helps to maximize the total annual energy yield. These are normally oriented towards the Equator, at a tilt angle slightly less than the latitude of the site. Note that the tilt angle or "inclination angle" is the angle of the PV modules from the horizontal plane. The orientation angle or "azimuth" is the angle of the PV modules relative to south; East is -90° south is 0° and west is 90°.

Fixed tilt mounting systems are simpler, cheaper and have lower maintenance requirements than tracking systems. Frames to carry the PV panels are built first, and then the PV panels are fixed on the frame as shown in Figures 10a-10c, [20].

(a)

(b)

(c)

Figure 13a-13c : Fixed mounting arrangement, [20]

Example of fixed mounted PVPS is the Five Points Solar Station, which has Capacity equal 17.7 MW DC in Fresno County, California. The Five Points project is part of PG&E's 250-MW Utility Owned Generation (UOG) PV Program, a five-year plan for the construction of utility-owned solar PV stations, [15].

b) Seasonally Adjusted Tilt

As the majority of the solar energy is in the direct beam, maximizing collection requires the sun to be visible to the panels as long as possible. The tilt angle can be mechanically adjusted seasonally to optimize output in summer and winter. The angle is usually adjusted twice or four times per year. These require more land area to reduce internal shading at the steeper winter tilt angle. Because the increased output is typically only a few percent, it seldom justifies the increased cost and complexity of this design. Figure 11 shows the arrangement of seasonally adjusted PV panels in photovoltaic power plant near Alamosa, Colorado. In this plant, the 82-acre tract site is one of the largest PV in the US. The Alamosa Photovoltaic Plant, which went on-line in December 2007, and generates about 8.2 megawatts of power.

Figure 14 : Seasonally adjusted fixed-axis photovoltaic panels at the Sun Edison photovoltaic power plant near Alamosa, Colorado

c) PV Panels tracking

Having the direct (beam) radiation, main part of the global radiation, perpendicular on the PV panel surface as much as possible maximizes the energy collected and thus the yield. The main factor affected the energy contributed by the direct beam is the cosine angle between the incoming light and the panel (angle i). The power lost due to deviation of this angle is given in Table 6, and Fig. 15.

Table 6 : Direct power lost (%) due to misalignment (angle i), [19]

I	Lost = 1 - cos(i)	*i*	hours	Lost
0°	0%	15°	1	3.40%
1°	0.02%	30°	2	13.40%
3°	0.14%	45°	3	30%
8°	1%	60°	4	>50%
23.4°	8.30%	75°	5	>75%

Trackers with accuracies of ± 5° can deliver greater than 99.6% of the energy delivered by the direct beam plus 100% of the diffuse light. Thus, high accuracy tracking is not usually used in non-concentrating PV applications.

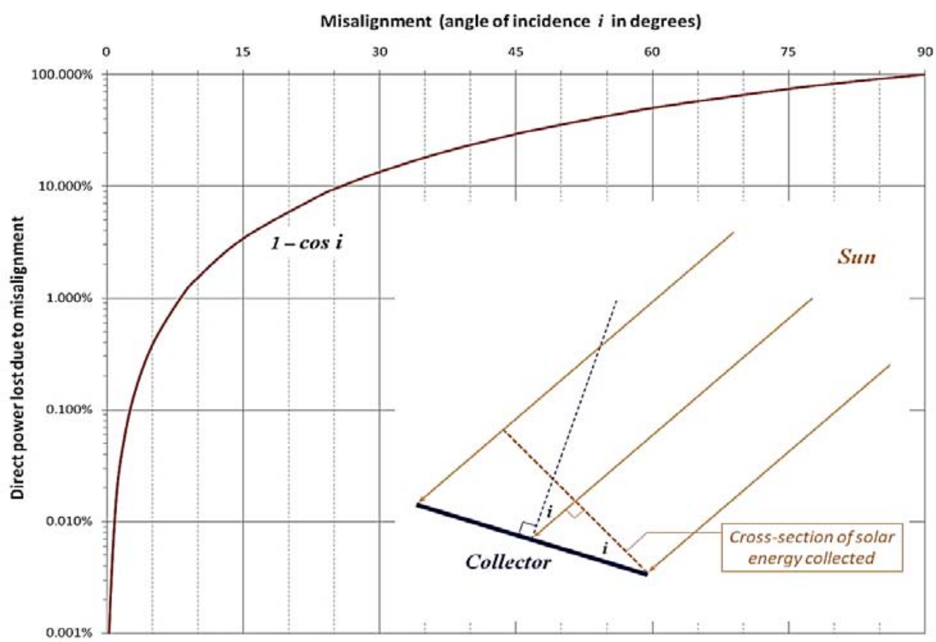

Figure 15 : The effective collection area of a flat-panel solar collector varies with the cosine of the misalignment of the panel with the Sun, [21]

Tracking will always result in a higher energy yield. The amount of the boost however is very much dependent on the location. Generally, locations with a higher proportion of direct sunlight will benefit more from tracking than locations with a high proportion of diffuse light such as Germany, see Table 4.

Table 4 : Boost of PV system by tracking, [20]

	Flat Panel horizontal surface	Fixed mounting, optimum angle	1-axis tracking	1-axis with seasonal adjustment	2-axes tracking
Energy boost in comparison to optimum tilt	-15%	0%	20%	26%	32%
Initial marginal cost per m^2	0%	5%	10%		20%

Tracking increases the performance ratio of a system. It also results in higher yields for the inverter. Dual-axis tracking systems increase the average total annual irradiation in locations with a high proportion of direct irradiation. Tracking systems follow the sun as it moves. Orienting the solar panels to be normal to the sun's rays maximizes the intensity of incoming direct radiation. The two axis tracking system enables tracking the sun in its daily orbit across the sky, and as its elevation changes throughout the year. The arrays have to be spaced out to reduce inter-shading as the sun moves and the array orientations change. So, it needs more land area. The maximum increased output can be of the order of 30% in locations with high levels of direct radiation, but the increase is lower in temperate climates or when diffuse radiation is significant, due to overcast conditions. Schematic increase of power output due to the use of dual axis tracking is shown in Figure 12.

Tracking systems are generally the only moving parts employed in a PV power plant. Single-axis trackers either alter the orientation or tilt angle only, while dual-axis tracking systems alter both orientation and tilt angle. Dual-axis tracking systems are able to track the sun more precisely than single-axis systems. Depending on the site and precise characteristics of the solar irradiation, trackers may increase the annual energy yield by up to 27% for single-axis and 37% for dual-axis trackers. Tracking also produces a smoother power output plateau, as shown in Figure 15. This helps meet peak demand in afternoons, which is common in hot climates due to the use of air conditioning units.

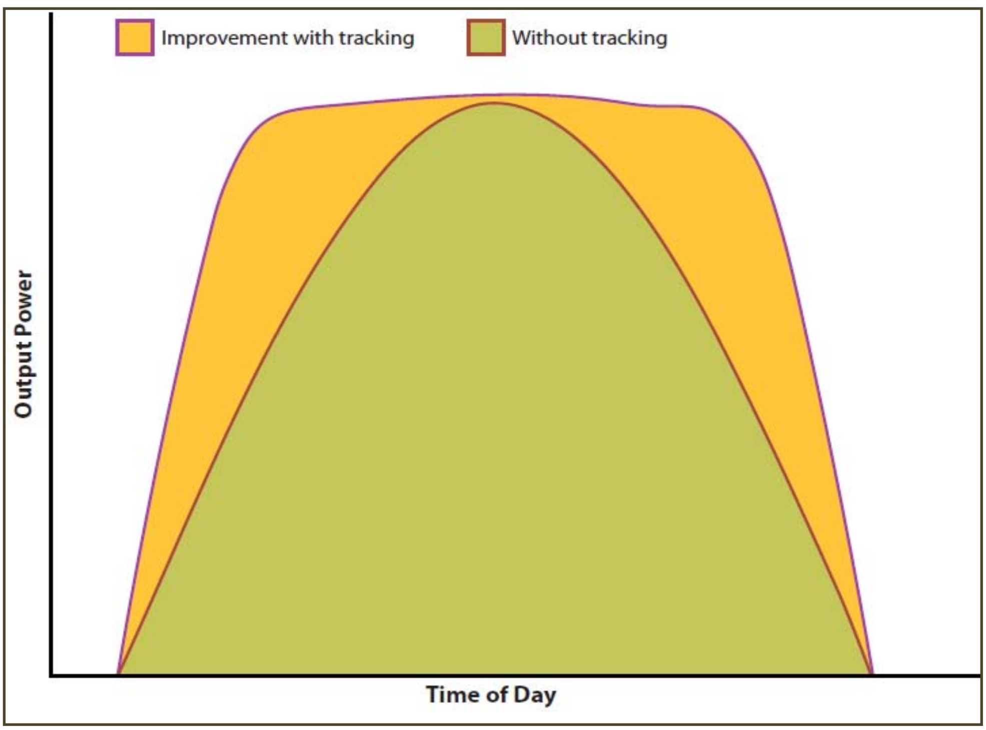

Figure 15 : Benefit of Dual Axis Tracking System, [1]

The tracking system needs additional capital costs for the procurement and installation of the tracking systems (typically $140-700/kWp); and added additional maintenance costs range from $2.8-21/kWp per annum, [1]. It also needs additional land area required to avoid shading compared to a free field fixed tilt system of the same nominal capacity. Almost all tracking system plants use crystalline silicon modules because their higher efficiency. This is reduces additional capital and operating costs required for the tracking system (per kWp installed). Examples of PVPS using dual axis tracking systems are: Bellpuig Solar Park near Lerida, Spain uses pole-mounted 2-axis trackers; and the Erlasee solar park installed by Solon Mover L plant of 12 MWp, shown in Figure 16.

Figure 16 : Azimuth-altitude dual axis tracker - 2 axis solar tracker, Toledo, Spain

Tracking the sun in one dimension can achieves some of the output benefits of tracking, with a less penalty in terms of land area, capital, and operating cost. A single axis tracker with roughly 20 degree tilt at Nellis Air Force Base in Nevada, USA is shown in Figure 14.

Figure 17 : Single axis trackers with roughly 20 degree tilt at Nellis Air Force Base in Nevada, USA. The arrays form part of the Nellis Solar Power Plant. Credit: U.S. Air Force photo by Senior Airman Larry E. Reid Jr,

VII. Economy of PVPS

a) Levelized Cost of Energy (LEC) of Solar PV Systems

The levelized cost of energy (LEC) of solar PV systems reflects the price at which energy must be sold to break even over the assumed economic life of the system. In other words, it is the cost incurred to install and maintain an energy-producing system divided by the energy the system will produce over its lifetime of operation:

LEC = Life time energy cost/ Life time energy generation

This equation yields a net present value in the familiar cents per kilowatt-hour (kWh) of electricity generated. This is an assessment of the economic lifetime energy cost and energy production and can be applied to essentially any energy technology. It is frequently used to evaluate a technology or energy system against electricity purchased from the grid. The LEC equation takes into account system costs, as well as factors including financing, insurance, operations and maintenance (O&M), depreciation and any applicable incentives. Installed costs are a primary driver for solar PV systems as they lack fuel costs and require minimal O&M.

By knowing that the EP produced by PVPS is higher than the EP retail price, it is required to identify if and when the declining LEC of solar PV intersects with the increasing retail electricity prices. The term frequently used to describe this intersection is "grid parity". The installed cost of solar PV systems is the largest component of the LEC.

The installed price of utility-scale systems varies significantly across projects. In the US, among 49 projects completed in 2011, for example, installed prices ranged from$2.4/W to $6.3/W, reflecting the wide variation in project size (from 2 MW to 35 MW), differences in system configurations (e.g., fixed-tilt vs. tracking and thin-film vs. crystalline modules), and the unique characteristics of individual projects, [20]. It is noticed that for very large PVPS plant of 187.5 MWP DC one-axis utility-scale ground mount, the estimated cost was $4.40/WP DC, or $ 5.9/W (by considering 0.75 De-rate Factor from DC to AC). So, for Qatar and 50 MW plant in Qatar if 20% increase is assumed the price would be $7.04, and the plant will cost 352 million (M). In another study for India, 169 Indian Rupee ($3)/W were reported. Again, if this for peak DC, and by considering 0.75 De-rate Factor from DC to AC it would be $4/W, [1].

A study to calculate the LEC by North Carolina State University indicated that for 10 MW plant made the following assumptions: the installed cost is $3.75 -$5/W, economic life of system is 20 years, fixed operation and maintenance is $50-65 kW/year, capacity factor 15-28%, the LEC is $0.24-0.46/kWh, [21]. The cost breakdown was given in Fig. 18.

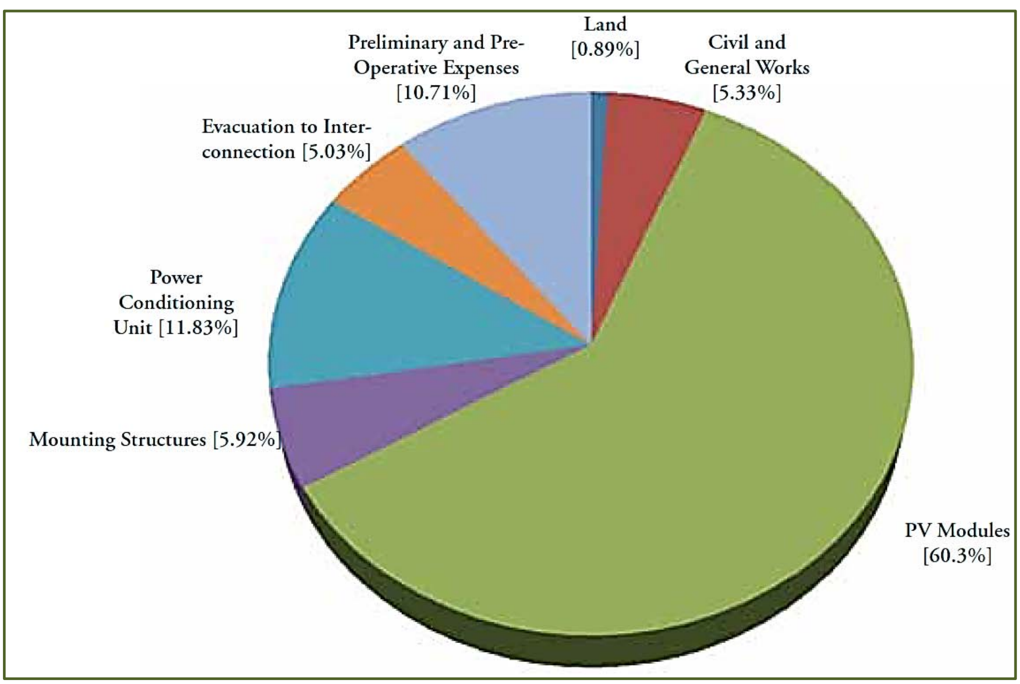

Figure 18 : Cost breakdown of PV power station, [21]

b) Utilities as Contractual Intermediaries

The utility in Qatar is acting as contractual intermediary agent between the power producer and the customers. The owner of the power plant sells power output from the plant (it is solar PV system here) to the utility, which, in turn, sells the power back to the site host/end-user.

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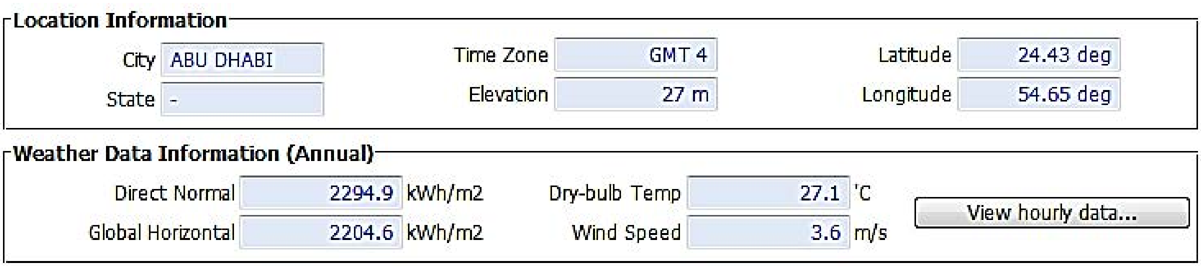
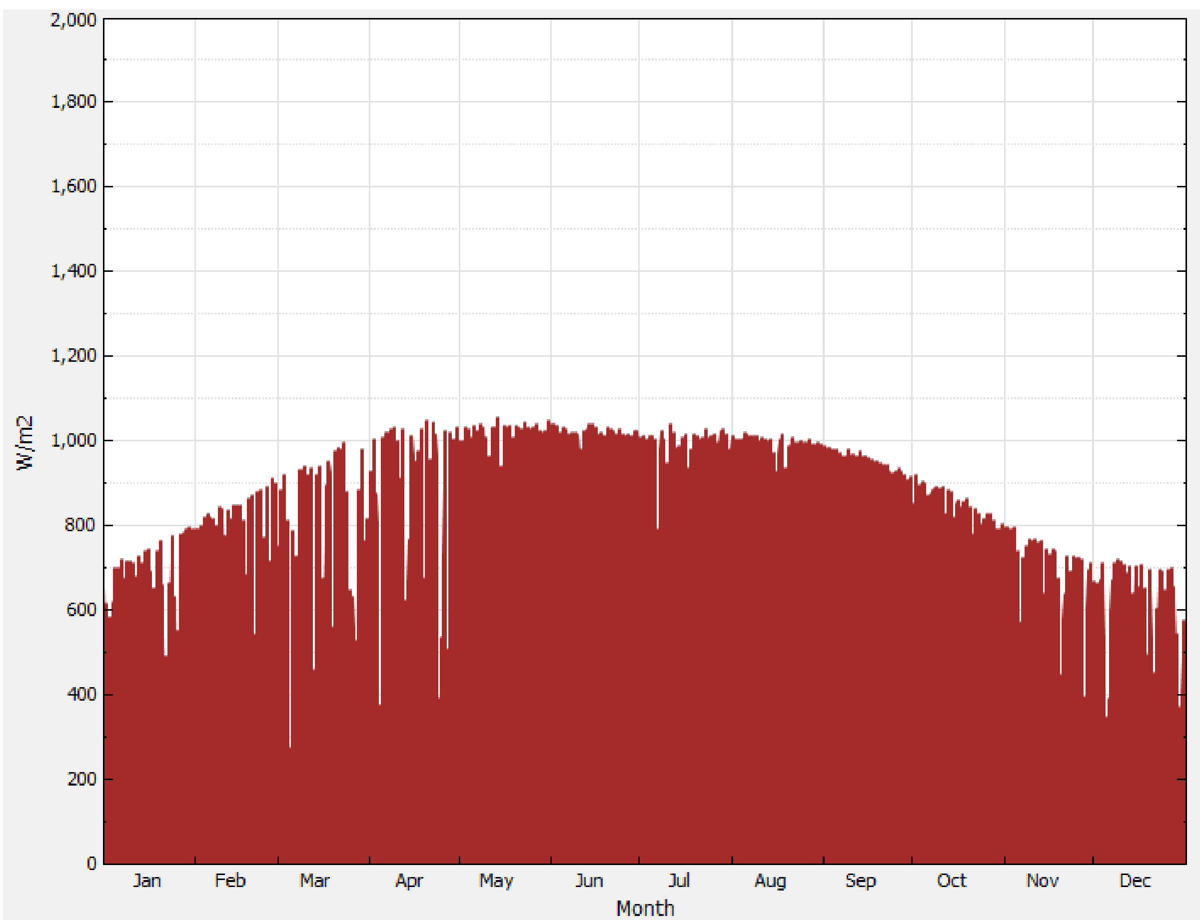
This arrangement protect consumers (rates and reliability) and to ensure a highly functioning electric grid. By having a single entity control the system, a utility can balance constantly changing supply and demand to ensure reliability and keep the electricity flow on the grid optimized and safe.

VIII. Suggested pvps using Flat type pv System and Sam Computer Program Results

A PV array of 20 MW_{dc} is suggested in this study. The System Advisor Model (SAM) computer program developed by NREL is used here to figure the PVPS characteristics, capital cost, and the EP output cost in $/kWh. Because no boundary conditions data are available for Qatar, the environmental data for Cairo, Egypt is used in running the program. This environmental data is given as follows:





Global Horizontal, W/m^2

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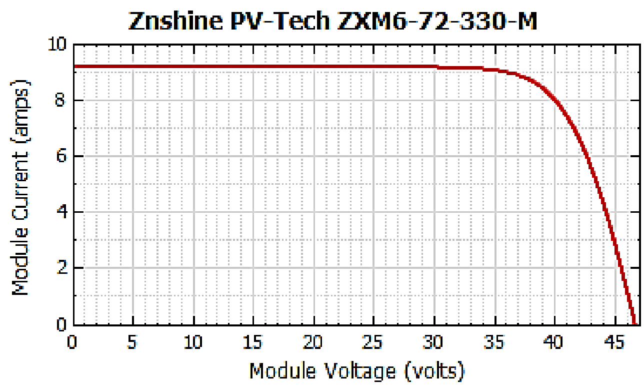
27

PV Module: Znshine PV-Tech ZXM6-72-330-M

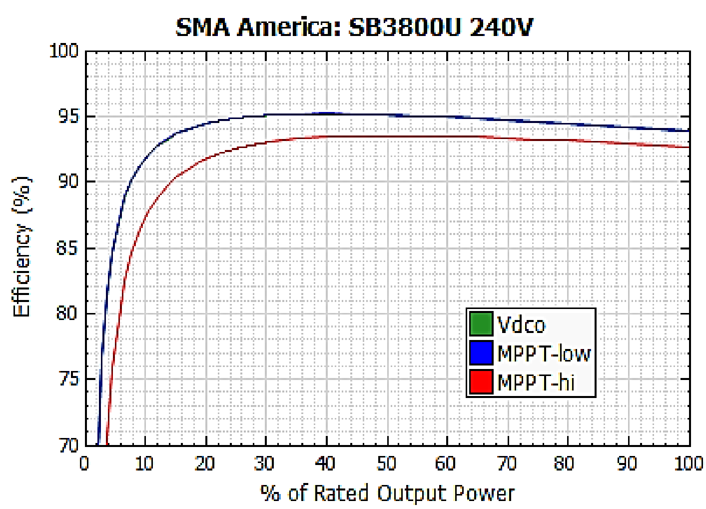


			Temperature Coefficients			
Efficiency	17.00	%				
Maximum Power (Pmp)	329.998	Wdc	-4.530e-001	%/C	-1.495e+000	W/C
Max Power Voltage (Vmp)	38.15	Vdc				
Max Power Current (Imp)	8.65	Adc				
Open Circuit Voltage (Voc)	46.72	Vdc	-3.200e-001	%/C	-1.495e-001	V/C
Short Circuit Current (Isc)	9.19	Adc	5.600e-002	%/C	5.146e-003	A/C

Physical Characteristics

Material	Mono-c-Si	Module Area	1.941	m2	Number of Cells	72

Inverter: SMA America: SB3800U 240V



CEC weighted efficiency	94.5729	%			
European weighted efficiency	94.2751	%			
Maximum AC power	3800	Wac	C0	-9.30559e-006	1/Wac
Maximum DC power	4050.67	Wdc	C1	5.66625e-005	1/Vdc
Power consumption during operation	24.7974	Wdc	C2	0.00268062	1/Vdc
Power consumption at night	0.161	Wac	C3	-0.000103656	1/Vdc
Nominal AC voltage	240	Vac			
Maximum DC voltage	600	Vdc			
Maximum DC current	18	Adc			
Minimum MPPT DC voltage	250	Vdc			
Nominal DC voltage	251.5	Vdc			
Maximum MPPT DC voltage	480	Vdc			

The array consists of 60646 modules of 117,702 m^2 total area, connecting by 7580 strings, or 8 modules per string. The nameplate capacity and Vmp are at module reference conditions. Voc (string) is 373.76 V at 1000 W/m^2 irradiance and 25°C, and Vmp (string) = 305.2 V. The module material is mono Crystalline Silicon (c-Si). The number of used inverters is 5500, V dc max (dc-inverter) 600 V. Data on module's dimensions are given as:

Actual Layout

Modules			Inverters		
Nameplate capacity	20011	kWdc	Total capacity	20900	kWac
Number of modules	60640		Total capacity	22278.7	kWdc
Modules per string	8		Number of inverters	5500	
Strings in parallel	7580		Maximum DC voltage	600	Vdc
Total module area	117702	m2	Minimum MPPT voltage	250	Vdc
String Voc	373.76	V	Maximum MPPT voltage	480	Vdc
String Vmp	305.2	V			

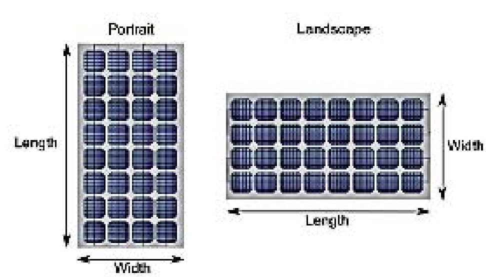
Nameplate capacity and string Vmp are at module reference conditions. String Voc is at 1000 W/m2 incident irradiance and 25 'C cell temperature.

Module

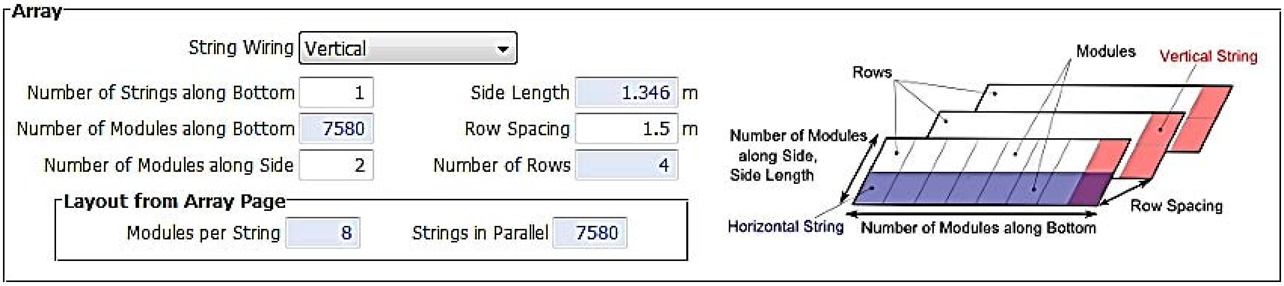
Orientation	Landscape	
Length	2.884	m
Width	0.673	m
Number of Cells along Length	12	
Number of Cells along Width	6	
Number of Bypass Diodes	3	

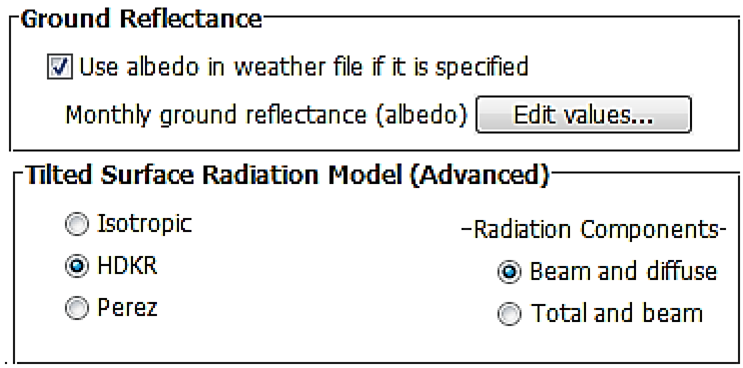
Characteristics from Module Page

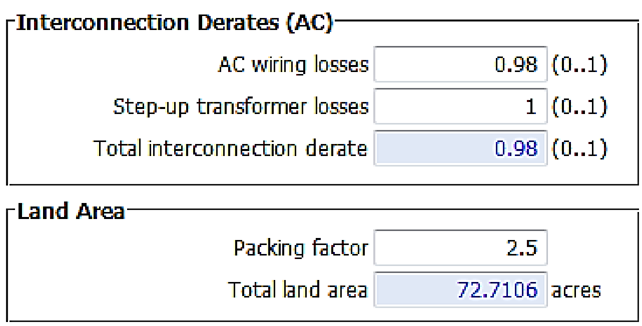
Area	1.941	m2	Number of cells	72



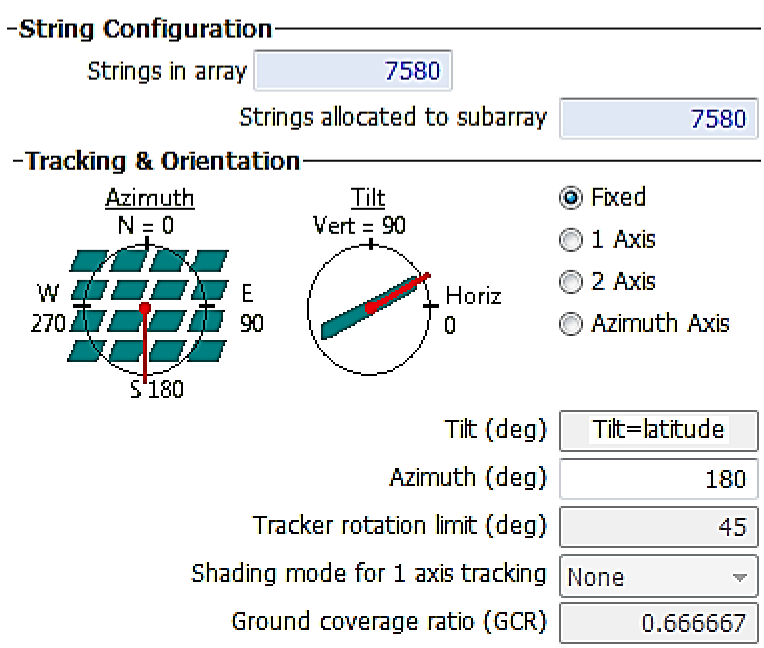
The string wiring is shown as follows:







The tracking and orientation are given as:



Details of capital cost are given by:
Direct capital cost

Direct Capital Costs

Module	60640	units	0.3	kWdc/unit	20011	kWdc	$ 3.302	$/Wdc	$ 66,076,481.82
Inverter	5500	units	3.8	kWac/unit	20900	kWac	$ 0.61	$/Wac	$ 12,749,000.00
Balance of system, equipment	0	$	0.458	$/Wdc	0	$/m2			$ 9,165,060.17
Installation labor	8100	$	0	$/Wdc	0	$/m2			$ 8,100.00
Installer margin and overhead	0	$	0	$/Wdc	0	$/m2			$ 0.00
							Contingency	0 %	$ 0.00
								Total Direct Cost	$ 87,998,641.98

Indirect cost

Indirect Capital Costs

	% of Direct Cost	Cost $/Wdc	Fixed Cost	Total
Permitting, Environmental Studies	0 %	0.00	$ 0.00	$ 0.00
Engineering	0 %	0.00	$ 800.00	$ 800.00
Grid interconnection	0 %	0.00	$ 0.00	$ 0.00

Land Costs

Total Land Area 72.7106 acres

	Cost $/acre	% of Direct Cost	Cost $/Wdc	Fixed Cost	Total
Land	0.00	0 %	0.04	$ 0.00	$ 800,441.94
Land preparation	0.00	0 %	0.20	$ 0.00	$ 4,002,209.68

Sales Tax of 5 % applies to 100 % of Direct Cost $ 4,399,932.10

Total Indirect Cost $ 9,203,383.72

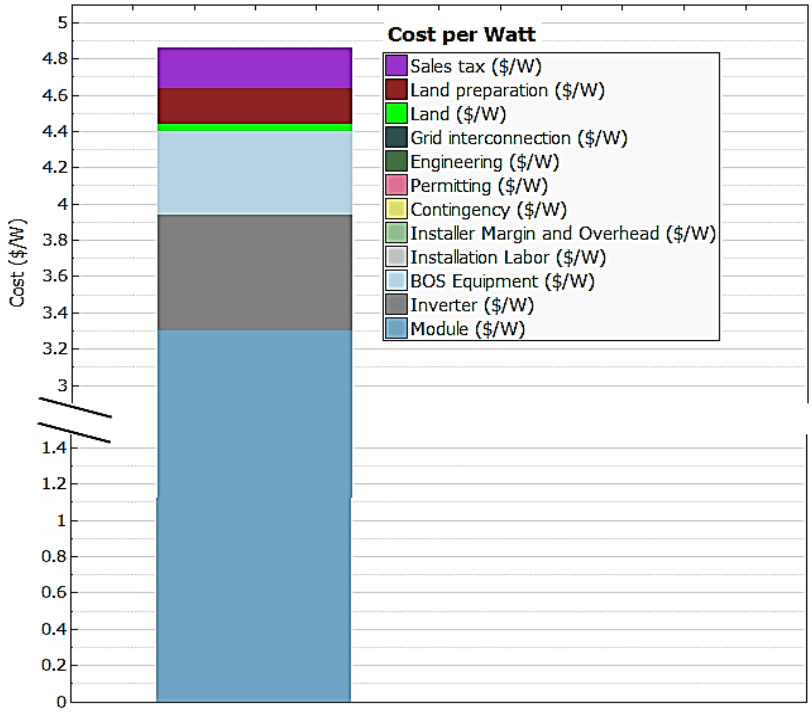
Total installed cost excluding any financing cost

Total Installed Costs

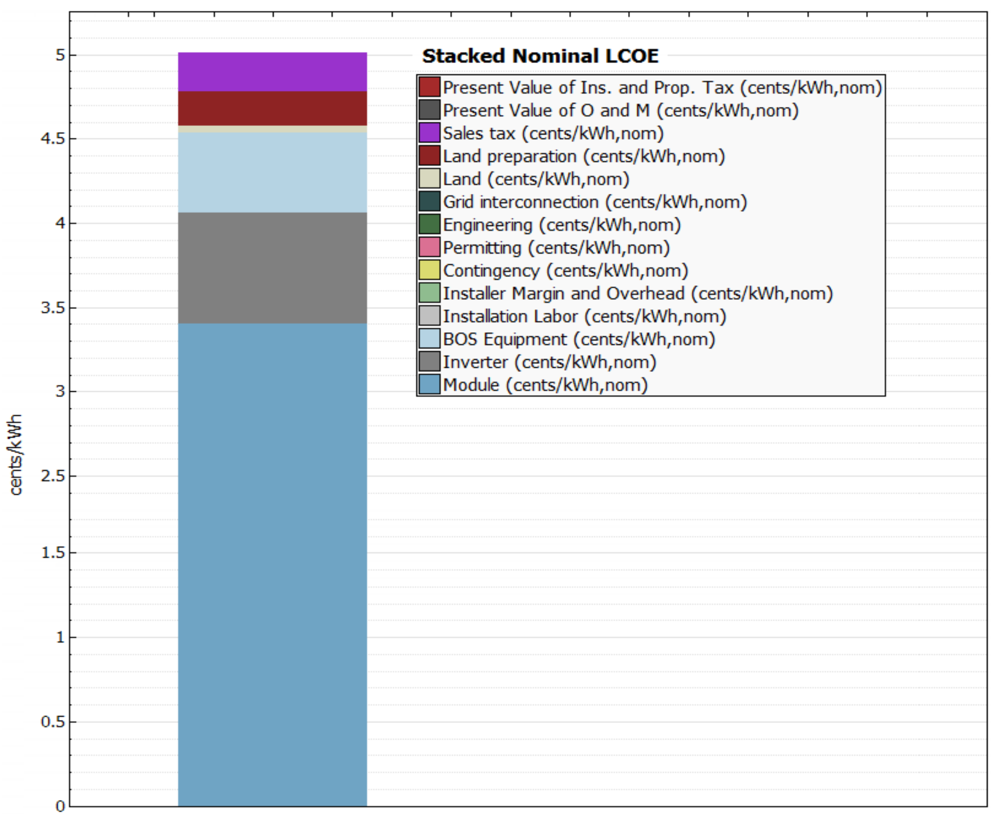
Total Installed Cost	$ 97,202,025.70
Total Installed Cost per Capacity ($/Wdc)	$ 4.86

Total Installed Cost excludes any financing costs

The itemized capital cost is given as:



The levelized Electricity Cost (LEC) is given as:



IX. Conclusions

The technology and economics of the PV power station is presented in this paper. The main components of the PV power plants including the solar PV modules, module mounting and tracking systems, inverters (or converters), and step-up transformers was outlined. It reviews the materials of the PV cells, the PV cells degradation, and the existing PV power plant. Utility PV power plants around the world were also reviewed.

The System Advisor Model (SAM) software developed by National Renewable Energy Laboratory (NREL) has been used to predict the total direct capital cost of the 20 MW PV plant as $88.0 million (M), and total installed cost as $ 97.202 M; or $4.86 M/MW. This is almost half the cost of the CSP using parabolic trough plants. The LCOE, as given by the computer program is $0.16/kWh. The main disadvantage of the PV power station is non-dispatch ability.

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