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PV Outdoor Tests

Rustu Eke

Abstract

The main purpose of this chapter is to survey the structure, operation, and design of photovoltaic (PV) systems. PV systems consist of solar cells and electronic units which convert directly produced electricity from solar irradiation to electricity in the form of demand by load or feed the produced electricity directly into the grid. The heart of the system is the solar cell or PV array. From individual solar cell to PV power plant and solar electricity conversion will be discussed in this chapter. Indoor and outdoor measurement of PV modules and performance of PV systems will be summarized. The performance of the system which is mainly the energy output depends on the operating condition, the location of the system, and the configuration of the system. The system modeling and its behavior under varying weather conditions which strongly affect the electricity output of the system will be discussed in this chapter.

Keywords: PV module, PV system, performance, indoor and outdoor measurements, PV electricity cost

1. Introduction

During the last few decades, there has been an exponential growth in photovoltaics across the world. Although market grows day by day and correspondingly employment rate increases, this brings many problems associated with the quality of the system due to several factors [1]. PV system installations have increased, and now in annual installations, PV is one of the leading power capacity additions. In 2018, over 100 GW of new PV power capacity was added. The annual PV capacity addition in 2018 was more than the total installed capacity in 2012. Total installed PV power capacity was in excess of 500 GW at the end of 2018 [2]. The power produced by a PV system depends on a range of factors which need to be examined when the system is designed [3]. These factors can be given such as operating conditions, the details of the configuration of the system, the location of the system, the amount of received solar radiation, the ambient temperature, and other climate-related aspects.

This chapter provides an introduction to the PV system configuration and the influences of these parameters on PV system performance.

2. PV system

There are two main classifications of PV systems. The first one is grid-connected where PV modules produce their maximum energy and they always feed the produced electricity in the form of local electricity grid. The other is stand-alone PV systems that operate independent from the grid, and they supply the electricity

for the specified load. In these types of systems, PV modules do not operate at their maximum. Thus, power and generated energy values are limited with the capacity of storage. Grid-connected PV system schematic is simple and given in **Figure 1**.

The grid-connected system is often classified into two as distributed and centralized systems. Small systems are generally distributed and have a capacity less than 100 kW. Most of these systems are installed on roofs or at the top (garage, patio, winter garden, etc.) or beneath the buildings. Although distributed systems are connected to low-voltage grid and meet the local load centralized PV systems which are connected at a higher voltage, the main purpose of them is feeding the general grid supply. There has been an increase on the side of grid-connected ratio since 2009 because of the high-efficiency ratio of the PV system with respect to stand-alone PV systems as well as simplifications and improvements in grid connections. According to the IEA PVPS data, grid-connected PV systems represented around 62% of the cumulative installed PV capacity at the end of 2017 where this ratio is only 22% in 2009 [4].

The stand-alone system operates independently from the grid and provides the power and electricity of the specified load or loads. There is a charge controller and a battery bank different from the grid connected to the PV system. Moreover the inverter operates in a different way. The charge controller controls the charging and discharging of batteries and consists of a maximum power point (MPP) tracker for operating PV modules at a maximum power. A schema of stand-alone PV system is given in **Figure 2** with different loads.

The hearth of the PV system is the solar cell itself where a range of semiconductors are used in solar cells. PV modules have to offer a high performance, a stability in operation, and good and low-cost manufacturability, and they have to perform a long lifetime. Electricity yield is important for PV modules. Currently the installations in the established PV market are dominated by crystalline silicon (c-Si, including mono- and multicrystalline silicon). Other commercial PV technologies in the market are cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), amorphous silicon (a-Si), and several hybrid designs. There are also different types of solar cells like organic and polymer-based cells and some multi-junction cells. Some of them are in the market with a small ratio, and they are classified in emerging PV technologies [5]. In terms of performance, the most important difference between the module types is the conversion efficiency which is the ratio of the electrical output and the amount of solar irradiation received to the solar cell or module plane. There is a continuing development in cell and module efficiencies under tests, and the results are periodically publicized in some journals, and the latest solar cell and module efficiencies are summarized in **Table 1** [6].

The other parameters affecting the PV system performance are spectral distribution of light, temperature coefficients of PV module, cell stability, encapsulation quality, shading effect, design of PV modules (wiring of PV modules, number of series-parallel-connected PV modules), and other components like inverter and wiring other than the PV modules, namely, balance of system (BOS) equipment.
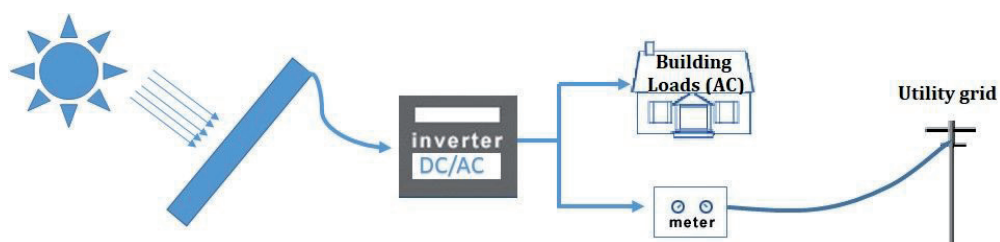

Figure 1.
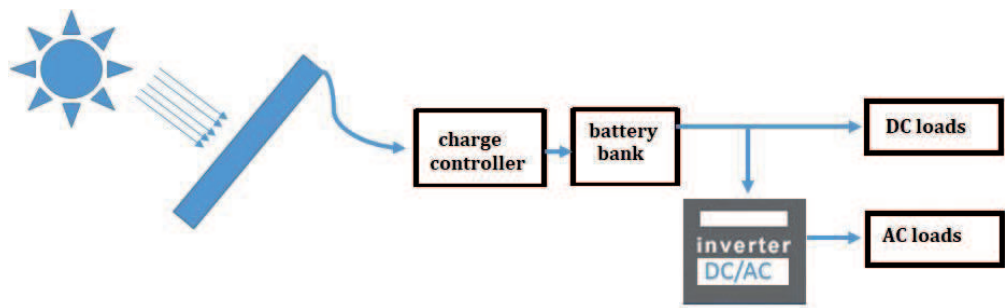*Schematic diagram of a grid-connected PV system.*

Figure 2.
Schematic diagram of a stand-alone PV system.

Module technology	Efficiency range under standard test conditions, large area (module efficiency) (%)	Highest reported laboratory efficiency, small area (%)
Crystalline silicon (sc-Si)	16–24.4	26.7
Multicrystalline silicon (mc-Si)	15–19.9	22.3
Amorphous silicon (a-Si)	6–11.9	14.0
CdTe	14–18.6	21.0
CIGS	15–19.2	22.9
Multi-junction	21–31.2	32.6
Organic	6–8.7	11.2

Table 1.
Solar cell and module efficiency ranges reported in late 2018.

3. PV system performance

Solar cells are the hearth of electrical conversion, and their electrical characteristics are similar with diodes. Therefore their current, I, and the voltage, V, relation will be given in Eq. (1):

$$I = I_o \left[exp\left(\frac{qV}{n k_B T}\right) - 1 \right] - I_L \tag{1}$$

Here, I_o is the reverse saturation current of the diode, q is the electron charge $(1.602 \times 10^{-19} C)$, k_B I the Boltzmann's constant $(1.38 \times 10^{-23} m^2 kg/s^2 K)$, T is the operating temperature in Kelvin, I_L is the light-generated current, and n is the diode quality factor depending on cell material.

In real devices, some parasitic resistances have to be defined. R_s is the series resistance for representing resistances related to carrier transport and ohmic contacts in material. R_{sh} is the shunt or parallel resistance representing leakages.

Under these acceptances I-V characteristics of a real solar cell can be given by Eq. (2):

$$I = I_L - I_o \left[exp\left(\frac{q(V + IR_s)}{n k_B T}\right) - 1 \right] - \frac{V + I R_s}{R_{sh}} \tag{2}$$

Solar cells can be connected in series or parallel to achieve higher current and voltage values. Only the values of current and voltage values can be changed in larger PV arrays. This equation can be applied to a variety of solar cell types. Only some

parameters (like diode quality factor) will show different values which cannot be physically described easily. But mathematically the equation overlaps the experimentally obtained values. As power is the product of current and voltage ($P = I \times V$), the current-voltage and power-voltage relation of a typical PV device can be given in **Figure 3**, where P_{max}, I_{mpp}, and V_{mpp} values are power, current, and voltage values of the desired device operating at its maximum power point (MPP).

Most of the PV module performance parameters are given in Eq. (2), and the resulting characteristics are given in **Figure 3**. I_{sc} is the short-circuit current when there is no voltage across the device and it is nearly equal to I_L. V_{oc} is the open-circuit voltage when there is no flow of current and it is the maximum voltage available from the device. In order to obtain the maximum power from a device, it'd operate round maximum power point (MPP). One of the other performance parameters of a PV device is the fill factor (FF) which is the ratio of power at MPP to I_{sc} and V_{oc} product. MPP also defines the efficiency of the device, and the efficiency is the ratio of power output to incident power falling on the surface of the device (Eq. (3)):

$$\eta = \frac{Power\ output}{Power\ input} = \frac{P_{max}(FF\,I_{sc}\,V_{oc})}{irradiation \times A} \tag{3}$$

where A is the total area of the device [6, 7].

Under ideal circumstances, PV devices operate at MPP, but in real operating conditions, PV devices operate round MPP, and most PV systems have maximum power point tracking units to operate with a minimum loss of power available from the device. In electrical connection of PV modules in forming PV arrays, it is very important to connect identical PV modules in the same lines for the best performance. Sometimes while designing the PV array, there should be some restrictions in obtaining uniform irradiation on the same array. If the PV modules do not have uniform irradiation, the electrically series-connected units obey the weakest one, and this results in a decrease in the output and loss of performance.

The output of the PV devices changes under operating conditions, so PV modules are produced and launched to the market according to the power values of the device obtained at a standard set of operating conditions. These conditions are standard test conditions (STC): irradiance of 1000W/m^2, standard global spectrum at air mass 1.5 and operating temperature of 25°C [6]. These conditions are the only test conditions and rarely found outside in the operating conditions. Irradiance is the level that defines the energy input of the system, and it varies throughout the day and the season. Spectrum of the light defines the amount of generated current of the device, and there will be a difference in the spectrum although the irradiance will be the same. The operating
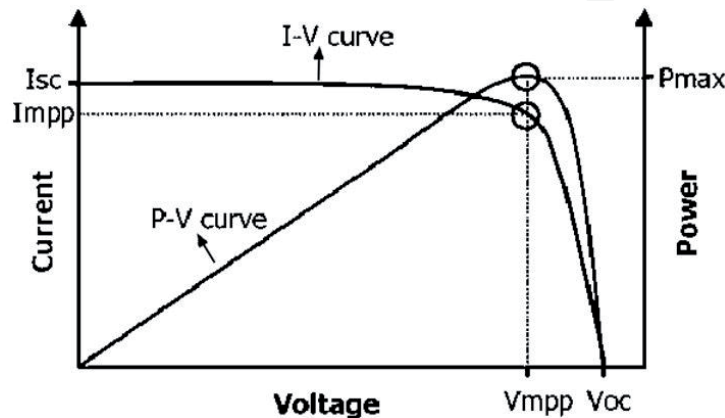

Figure 3.
The current-voltage and power-voltage characteristics for a solar cell/PV module/array.

temperature of the device is very variable, and it is generally over the value at STC. This high temperature depends on several factors like ambient temperature and plane of array solar irradiance level (G_{POA}) in W/m^2. Usually, the nominal operating cell temperature (NOCT) is given because of the difference at operating temperature in the field from STC values. These conditions are 800W/m^2 irradiance level, 20°C ambient temperature, 1 m/s wind speed, and under no load. NOCT values are usually given in PV module datasheets, and temperature is generally taken between 45°C and 50°C. The relation to find module operating temperature under NOCT is given in Eq. (4) [8]:

$$T_{module} = T_{ambient} + \frac{G_{POA}}{800}(NOCT - 20) \tag{4}$$

3.1 PV system efficiency and yield

PV device/module efficiency and performance parameters are given above. But a PV system consists of other components. For this reason, these components' efficiency values have to be taken into account while calculating the system efficiency. The end user is interested in the electricity produced by the PV system and its lifetime under real operating conditions because this directly influences the payback period or return time of the investment. The commonly used energy-rating standard for PV modules is given by the International Electrotechnical Commission (IEC) with IEC61853 (PV performance testing and energy rating part 1) [7]. Also the location of the system has to be considered while sizing the PV system. Energy yield measurements of PV systems at different climatic locations play an important role in the validation of the energy rating standard, deeper understanding of PV performance, and lifetime. Long-term and accurate measurements under real operating conditions are necessary, but there is currently no standard on how these measurements should be performed [9]. Most analyzers use inverter output or meter data for calculating the performance of PV systems. If the system is stand-alone, some other parameters like night loads and loss of load probability have to be regarded while designing the system. Energy yield and performance ratio (PR) values are the other parameters which defines the system's overall performance. Only PV efficiency is given in Eq. (3), but the power output of the whole system and calculation of efficiency using this output is very important, considering the other losses like wiring losses and inverter losses. In grid-connected PV systems, electricity output, solar resource, and system losses are the main parameters. Accurate evaluation of PV system performance is critical for PV industry.

Performance ratio defines the performance of the system [10, 11]. It is dimensionless and given as the ratio of Y_F, final yield, and Y_R reference yield. In general PR value of the system is calculated in a monthly or yearly basis. Sometimes this value will be calculated for small intervals such as daily or weekly, but greater interval is preferred. As in some seasons because of the high module operating temperature and high irradiance values, PR values will be calculated high, and generally this value is between 0.60 and 0.80:

$$PR = \frac{Y_F}{Y_R}(dimensionless) \tag{5}$$

where the final PV system yield Y_F is the ratio of net electricity output, E_{out}, of the PV system to the nameplate DC-installed power, P_o

$$Y_F = \frac{E_{out}}{P_o}(\text{kWh/kW}) or \ (\text{h}) \tag{6}$$

And the reference PV system yield Y_R is the ratio of H_t total plane of irradiance to G reference irradiance(**e. g. 1000W/m^2**):

$$Y_r = \frac{H}{G}(\text{h}) \tag{7}$$

Long-term PR calculation takes the system failures into consideration so it gives better results. But PR is neglected by some researchers, and only the electricity output per installed power is taken into account. Namely, they calculate only kWh/kWp ratio where kWp is the installed DC power capacity of the system [12].

Instead of defining the overall performance of the system, sometimes it is useful to consider the specific performance of a certain part of the system to find the correct design. Sometimes the output will not match the expectations. It will be PV array output or PV system output. In that situation, some modules, wirings, or other components will be analyzed. Most inverters give DC and AC power values at a certain time, so it is easy to calculate their exact efficiency. PV system operates during the daytime, so inverters also operate and their output values also vary. In semi-cloudy days, sometimes there should be a sudden decrease and increase in the irradiation level, and this causes a big difference in electrical value. Also the inverter efficiency varies sharply. At low irradiation levels, inverter efficiencies are low, but generally after 15% of their nameplate power, their efficiency is round 90%. Because of the variation in the irradiation level, input and output power, a new efficiency classification is defined in inverter efficiency calculation. It is Euro Efficiency or California Energy Commission (CEC) efficiency. Both are weighed efficiency values, and they use different efficiency values at different power input values and give lower than the peak efficiency but more representative values.

4. PV module characterization

The output of a PV system depends on various parameters, but one of the most important parts is the PV modules used. The electrical performance and output are given in Section 3 with module characteristics. Whether these characteristics are taken in laboratory conditions or in outdoor conditions, it is possible to translate the parameters to STC values and compare the nameplate values. A typical setup for laboratory I-V curve measurements is shown in **Figure 4**. The setup consists of a light source, a reference device for the determination of irradiance during the measurement, some temperature sensors, and an electronic load [12]. Measurement systems also include software for collecting the measured data and translating the desired values to STC with existing I-V curve with given parameter coefficients.

It is well known that PV modules operate under a wide range of temperature, irradiation level, angles of incidence of the sunlight, and spectral distribution. All these conditions affect the electricity output of the PV module. The temperature dependency of the PV module can be determined from the I-V curves at different temperature values and constant irradiance values in laboratory tests. In a similar line with these temperature dependencies, irradiance dependency, spectral response, and thermal behavior characteristics can be determined. There are a lot of universities and research labs all over the world that use several setups for measuring I-V at indoor, but it is not so easy to control and arrange some outdoor parameters. Generally, some meteorological parameters are used in the calculations and measured in different setups, or they can be included in the I-V curve measurement system shown in **Figure 5**.
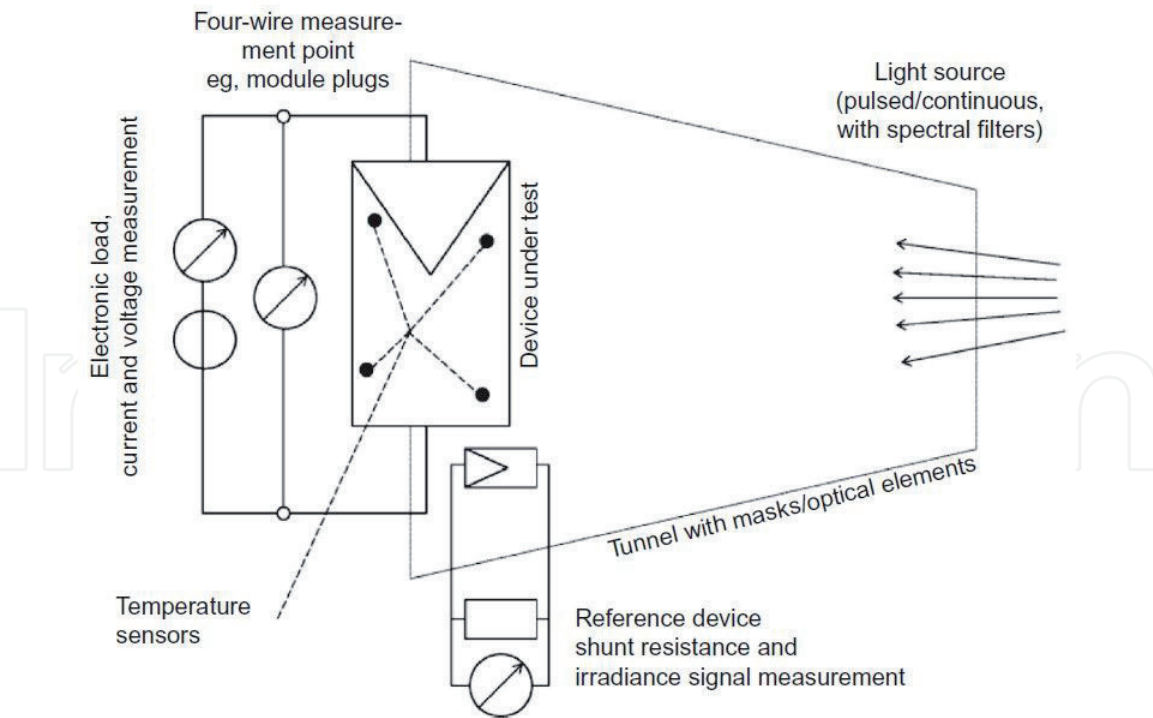
Figure 4.
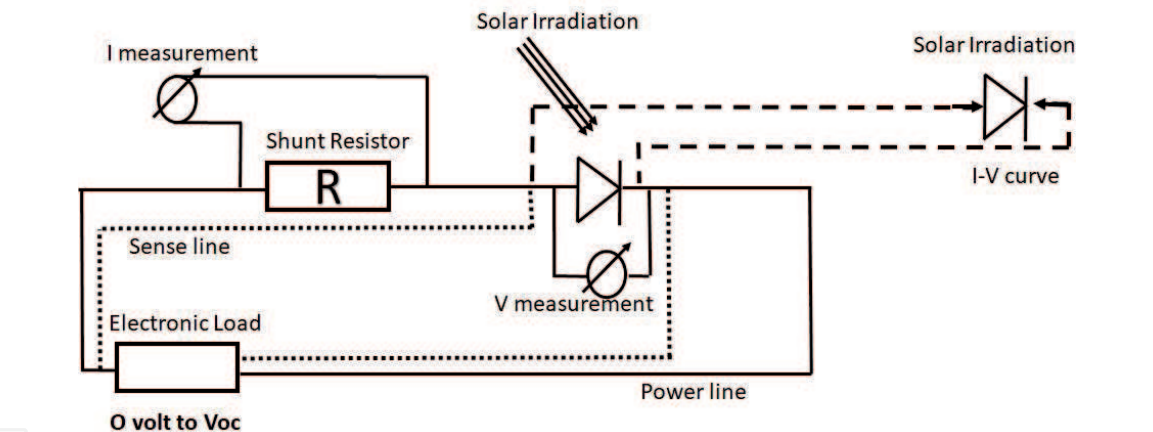*Schematic setup for I-V curve measurements at laboratory [13].*

Figure 5.
Schematic setup for I-V curve measurements at outside.

In some measurements, sense measurements are not used, but the presence of sense measurements supports the accuracy of the collected data. And, current measurements are evaluated with a precisely known value of shunt resistors. These sets of measurements increase the accuracy of the data. It is also difficult to get data close to short circuit, because the presence of a load complicates collecting data. An external power supply helps overcoming this problem, and researchers get more precise data for drawing the I-V curve and determining the PV module parameters [14].

5. Prediction of PV yield

PV module characterization methods are outlined in Section 4. Computer simulation tools are used to predict the electricity production of PV systems which are necessary for economic decisions [15]. Some input parameters like operation situations, environmental conditions and the location of the system are
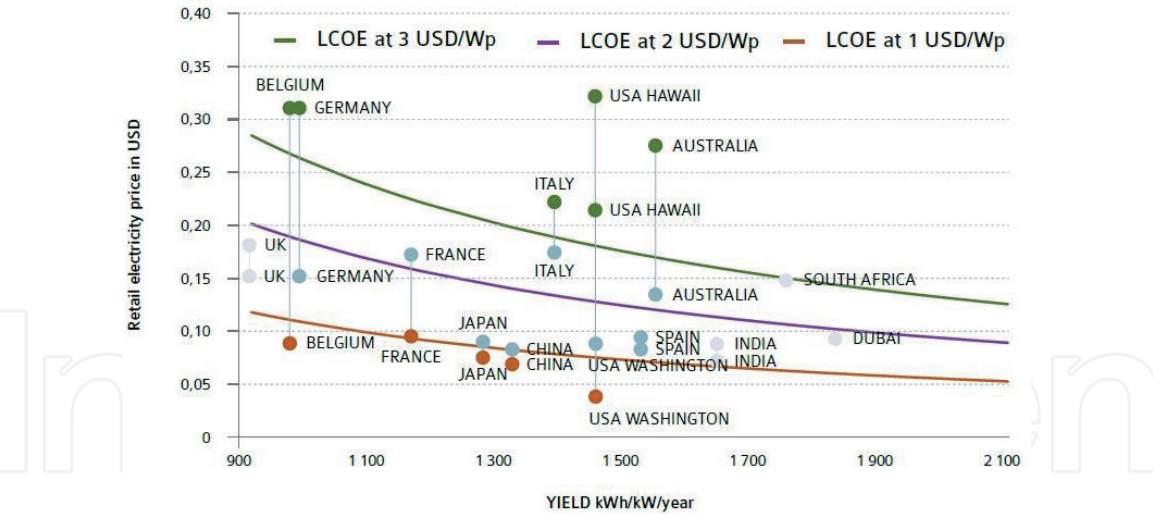
Figure 6.
PV electricity cost as a function of solar irradiance [4].

necessary for characterizing PV module and for electricity output of the system. The required number of input parameter depends on the complexity of the tool. The prediction of PV electricity yield is very important. Different technologies are used in PV systems [16–18]. Crystalline silicon technology based on PV modules dominates the market. Besides, there are other technologies which are used as PV modules that depend on the location of the installation and amount of electricity produced and meet in seasons. In sunny and coastal regions in summer, thin-film PV modules will perform better than crystalline silicon PV modules, while in high locations and during winter season crystalline silicon-based PV modules perform better than thin film because of the temperature coefficients. To understand technological differences and over or under performance of one technology with respect to other under specific climatic conditions, not only the power under STC is enough. It should be necessary to know the quality and the performances of other equipment in PV system [9]. Most of the people (users or investors) mind only the electricity yield while they decided to install a PV system. For grid-connected PV systems, electricity cost (levelized cost of electricity (LCOE)) has to be comparable with grid prices. For increasing the PV electricity usage or produc-ing PV system equipment, there are different support schemes in countries. This support appears sometimes in tax incentives sometimes like feed in tariff (FiT) and sometimes in self-consumption or various schemes. Grid parity is caught for several countries which have higher annual irradiation and sometimes different supporting schemes like self-consumption are applied. For the other countries, there are different support schemes for declining electricity cost. LCOE as a func-tion of solar resource for some countries are given in **Figure 6** [4]. Installation cost per kW-dependent LCOE is also given in **Figure 6**. LCOE depends on PV system size and location, so retail prices for some countries are wide (e.g., USA; although PV system has the same size, electricity prices are in the range of 0.04–0.32 USD).

6. Conclusions

In this chapter, PV electricity and the characterization methods used to deter-mine PV module are summarized. PV performance measurement methods and electricity cost per installed power is discussed. Although installed PV capacity on earth is about 500 GW, PV contribution to global electricity demand is still less than

3%, PV installation cost continues to decrease, and the main point is the cost of PV electricity. In order to be competitive with the market prices, PV electricity cost will have to be as low as it. This will be achieved with large-scale PV installations, low installation costs, and low maintenance cost.

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