ALMUSTAQBAL UNIVERSITY
Iraq - Babylon

RENEWABLE ENERGY TECHNOLOGY

Sustainable Path For a Carbon Free Future

Refrigeration and Air conditioning Techniques Engineering Department

Subject : Renewable Energy

Grade: 4th Class

Lecture:13

Photovoltaic technology

Dr.Eng. Azher M. Abed

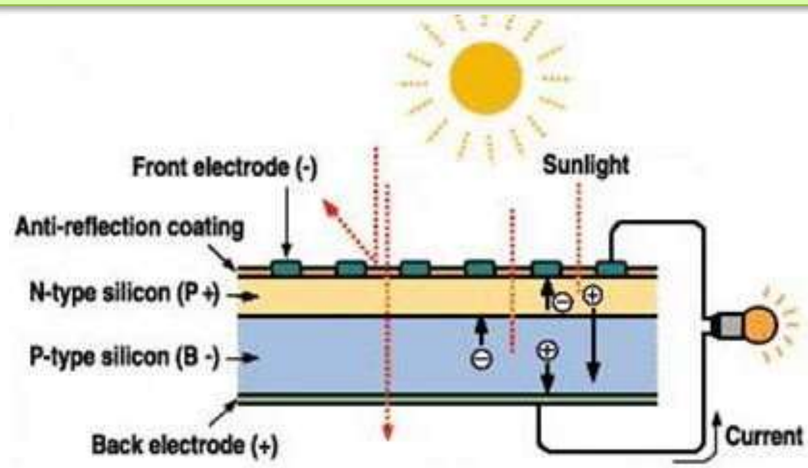
Dr. Haleemah J. Mohammed

2023-2024

Title: Photovoltaic technology

1. Introduction

- **Photovoltaic (PV) (photo = light, voltaic = electricity**: Is (usually) a semiconductor-based technology that converts light energy directly into electricity (DC electrical current and voltage), which either can be used immediately or stored, as in a battery, for later use.
- **A typical silicon PV cell is composed of the following:**
  - A thin wafer of silicon doped with phosphorus: (n-type) silicon.
  - A thicker layer of silicon doped with boron: (p-type) silicon.
  - An electrical field created where these two materials are in contact, called the p- n junction.



Semiconductor materials such as silicon, gallium arsenide, cadmium telluride or copper indium diselenide are used in these solar cells. The crystalline solar cell is the most commonly used variety.

6.2 Solar Cell Types

The following are the different types of solar cells

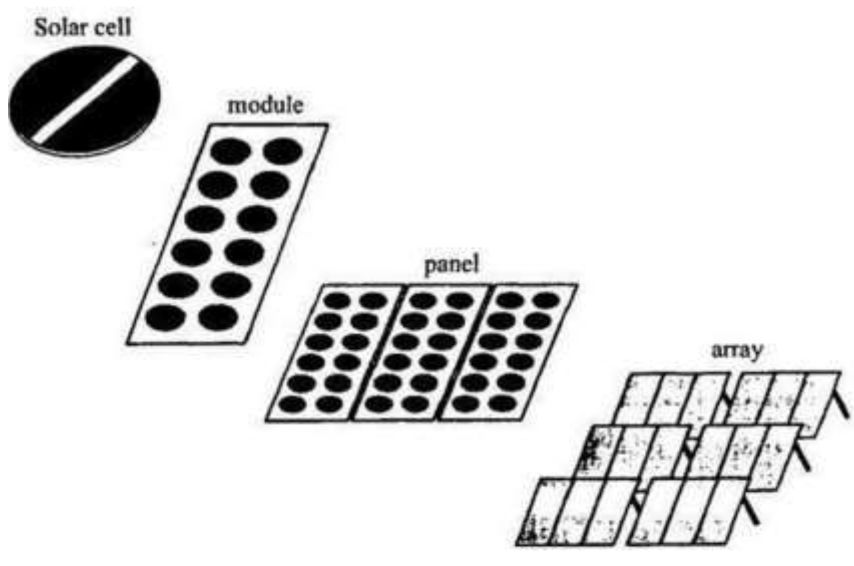
1. **Silicon Based Solar Cell (90 %) :** One silicon solar cell produces 0.5 volt**.**
2. **Thin Film(10 %) (Cadmium telluride (CdTe), copper indium gallium diselenide (CIGS)) :** Thin-film technology has always been cheaper but less efficient than conventional c-Si technology**.**
3. **Organic Solar Cell** or **plastic solar cell :** is a type of photovoltaic that uses organic electronics, a branch of electronics that deals with conductive organic polymers or small organic molecules

6.3 Module, Panel and Array

Module: PV cells are connected electrically in series and/or parallel circuits to make a module to produce higher voltages, currents, and power levels.

Panel: PV panels include one or more PV modules assembled as a pre-wired, field-installable unit.

Array: A PV array is the complete power-generating unit, consisting of any number of PV modules and panels.



6.3 PV array systems and PV applications

Photovoltaic (PV) systems can be grouped into stand-alone systems and grid connected systems. In stand-alone systems the solar energy yield is matched to the energy demand. Since the solar energy yield often does not coincide in time with the energy demand from the connected loads, additional storage systems (batteries) are generally used. If the PV system is supported by an additional power source – for example, a wind or diesel generator - this is known as a photovoltaic hybrid system. In grid-connected systems the public electricity grid functions as an energy store. In Germany, most PV systems are connected to the grid. Because of the premium feed-in tariff for solar electricity in Germany, all of the energy they generate is fed into the public electricity grid. The forecast for the next 40 years is that photovoltaics may provide up to one third of the power supply in Germany. While more and more grid-connected PV systems will be installed in Europe and North America in the coming years, in the long term it is expected that ever-increasing numbers of stand-alone systems will be installed, especially in developing countries. Small individual power supplies for homes - known as solar home systems – can provide power for lights, radio, television, or a refrigerator or a pump. And, increasingly, villages are gaming their own power supplies with an alternating current circuit and outputs in the two-digit kilowatt range.

1. Stand-alone systems

The first cost-effective applications for photovoltaics were stand-alone systems. Wherever it was not possible to install an electricity supply from the mains utility grid, or where this was not cost-effective or desirable, stand-alone photovoltaic systems could be installed. The range of applications is constantly growing. There is great potential for using stand-alone systems in developing countries where vast areas are still frequently not supplied by an electrical grid. But technological innovations and new lower-cost production methods are opening up potential in industrialized countries as well. Solar power is also on the advance when it comes to mini-applications: pocket calculators, clocks, battery chargers, flashlights, solar radios, etc., are well known examples of the successful use of solar cells in stand-alone applications. Other typical applications for stand-alone systems: (i.e. :consumer products, telecom, leisure, water pumping, lighting & signalling, rural electrification, etc.

➢ Components of stand-alone PV system

Stand-alone PV systems generally require an Energy storage system because the energy generated is not usually (or infrequently) required at the same time as it is generated. (i.e. solar energy is available during the day, but the lights in a stand-alone solar lighting system are used at night). Rechargeable batteries are used to store the electricity. However, with batteries, in order to protect them and achieve higher availability and a longer service life it is essential that a suitable charge controller is also used as a power management unit. Hence, a typical stand-alone system comprises the following main components:

1-PV modules, usually connected in parallel or series-parallel; 2-charge controller; 3-battery or battery bank; 4-load; 5-inverter - in systems providing alternating current (AC) power

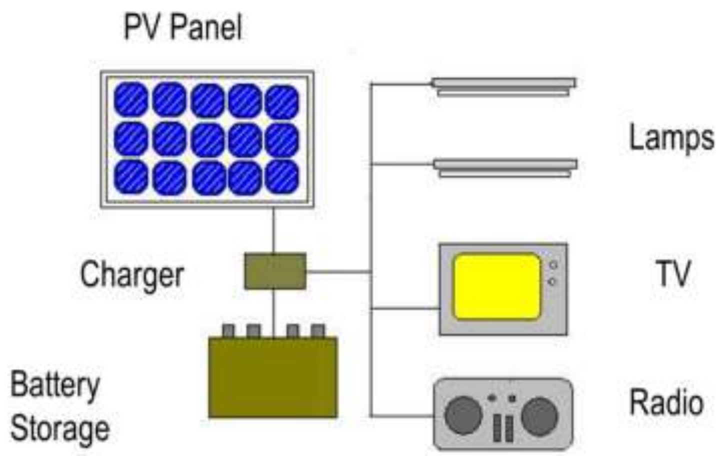


Fig: 6.1 stand-a lone systems

6.3.2 Grid-connected systems

A grid-connected PV system essentially comprises the following components :

1PV modules/array (multiple PV modules connected in series or parallel with mounting frame.

2PV array combiner/junction box (with protective equipment) ; direct current (DC) cabling ;
3 DC main disconnect/isolator switch ;
4 inverter ;
5 AC cabling ;
6Meter cupboard with power distribution system, supply and feed meter, and electricity connection.

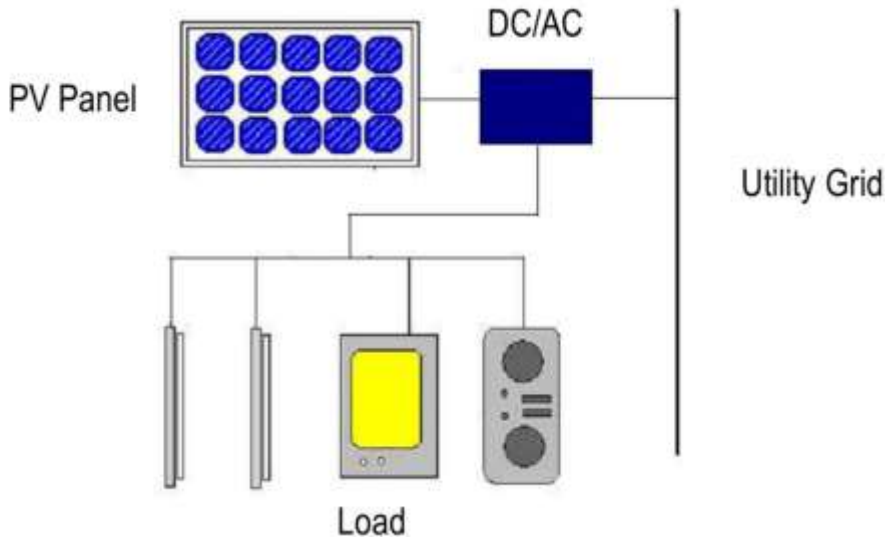


Fig: 6.2 grid-connected PV system

6.4 Effects of Radiation Intensity on Module Output

Solar cell module output is very much governed by the intensity of the solar radiation on a module. Figure 6.3 shows that module output is directly proportional to the solar irradiance. Halving the intensity of solar radiation reduces the module output by half. Lower radiation also lowers the voltage at which current is produced. Look at the I-V curves in Figure 6.3 &.4: a 50 % drop in insolation causes a 50 per cent drop in current. Cloud cover reduces the power output of a module to a third or less of its sunny weather output. During cloudy weather, the voltage of a module is also reduced. In hot, cloudy weather modules charging 12V batteries should be selected so that they maintain a high voltage – make sure they have 36 cells.

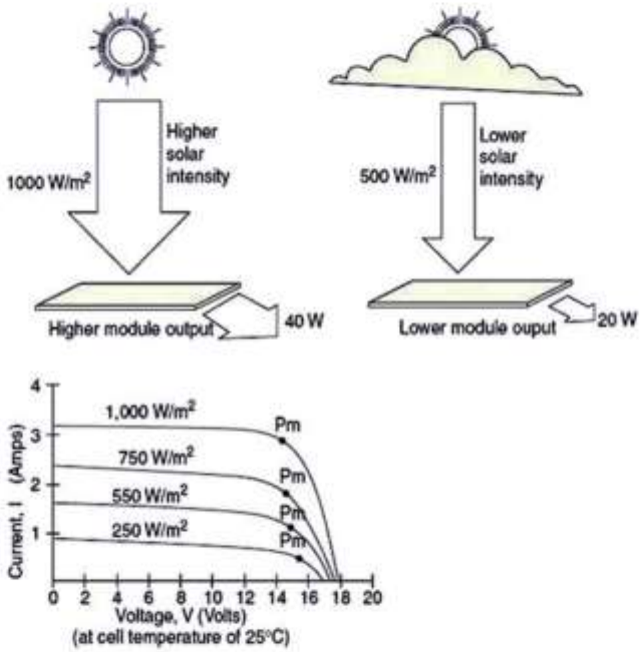


Fig 6.3 shows that module output is directly proportional to the solar irradiance

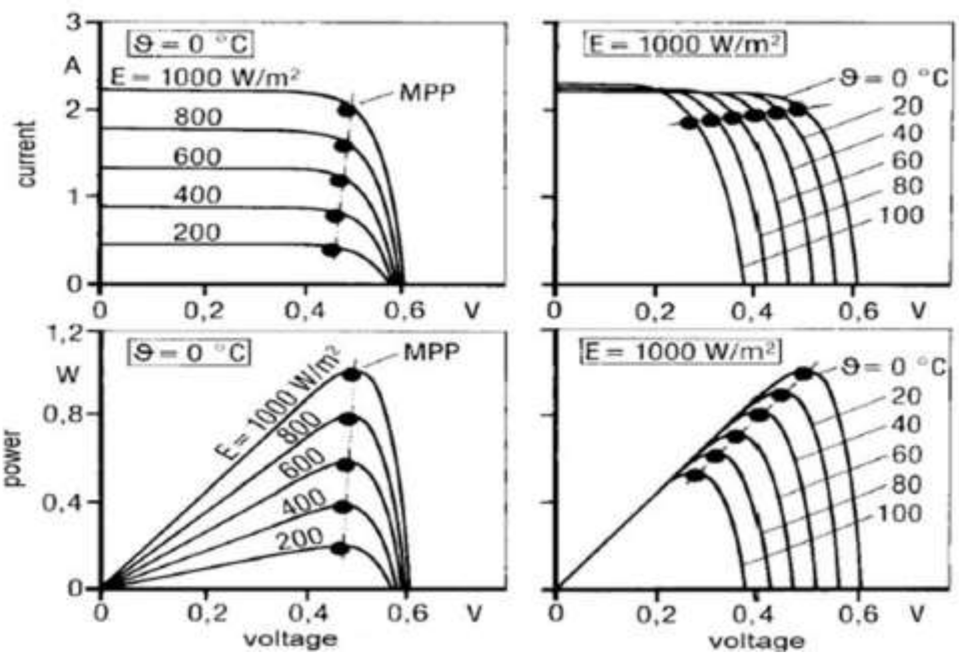


Fig 6.4 Effect of the Temperature and the Solar Radiation on PV output power

6.5 Performance of PV module

PV module is the electricity generator in PV system. PV module consists of a number of solar cells and these cells are connected in series and parallel circuits on a panel (module). The area of solar cell is order of few square inches and the area of the module is order of several square feet. The efficiency of the PV module is the important parameter in the module which represents the ratio between the PV power output and the global solar radiation input. Nowadays, PV modules with 18% efficiency are available in the market with reasonable cost. For example, a SANYO (HIP-215NHE5) PV module has efficiency 17.2%. This module has maximum power output about 215 W when the global radiation is 1000 W/m2 and with area about 1.25 m^2.Table 1 shows the manufacturing specifications of the PV module which are under standard laboratory test conditions (Air mass 1.5, Irradiance = 1000 W/m2, Cell temperature = 25°C) .

The maximum power output (Pmax) of the PV module under the site weather conditions can be estimated by the following equation:

$$P_{max}(G, T_c) = I_{sc}(G) \times V_{oc}(T_c) \times FF \quad (1)$$

Where Isc is short circuit current, Voc is open circuit voltage, and FF is fill factor .

It is clear from the Eq. 1 that the short circuit current is proportional to the irradiance (G) and the open circuit voltage is proportional to the cell temperature (Tc). The practical short circuit current and practical open circuit voltage at the site are given

$$I_{SC}(G) = I_{SC}(at\ 1kW/m^2) \times G\ (in\ kW/m^2) \quad (2)$$

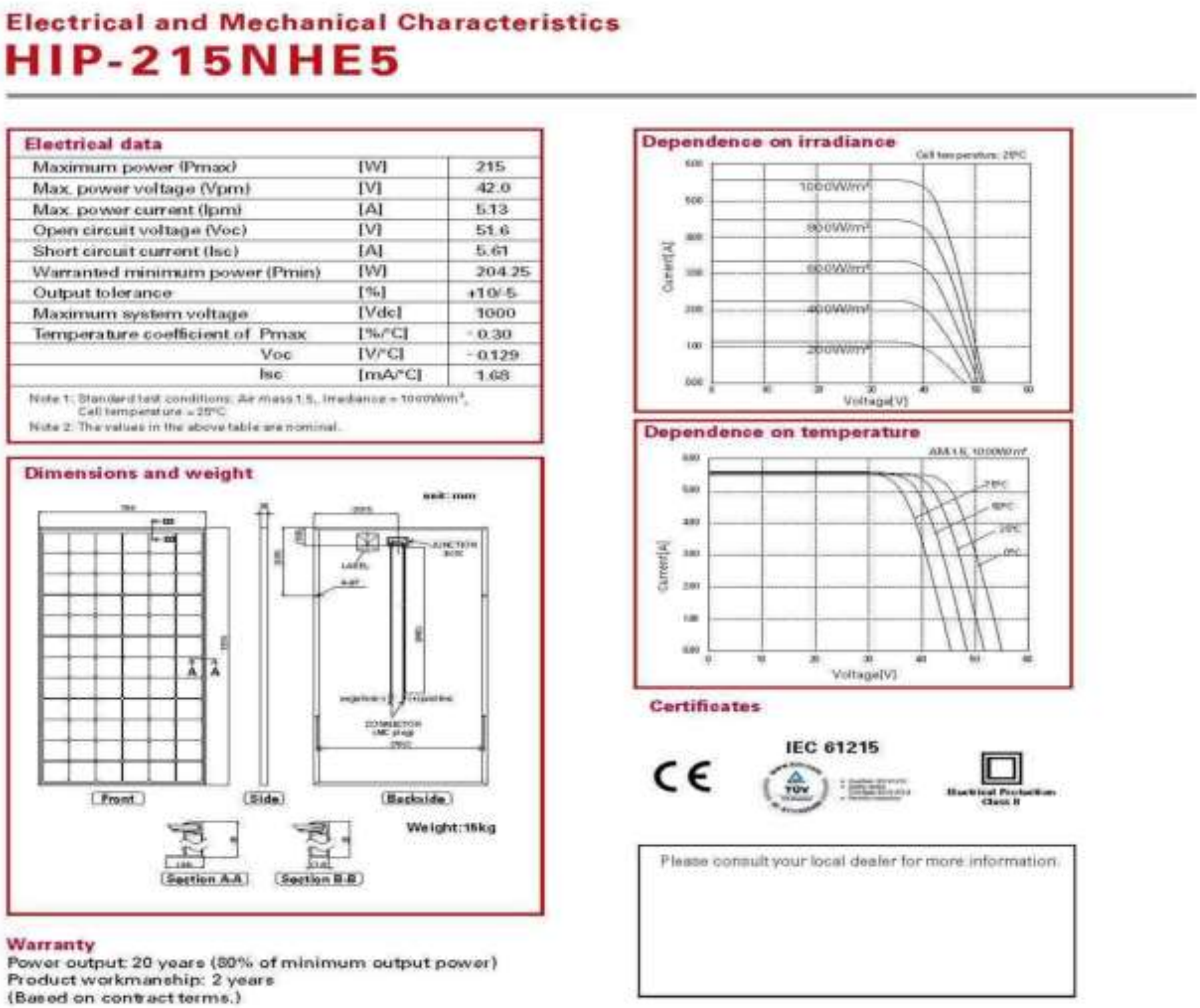
$$V_{oc}(T_c) = V_{oc} - 0.0023 \times number\ of\ cells \times (T_c - 25) \quad (3)$$

The cell temperate (Tc) is determined by

$$T_c = T_a + \frac{NOCT-20}{0.8} G(kW/m^2) \quad (4)$$

Where NOCT is normal operating cell temperature (usually between 42oC and 46oC), and *T*a is ambient temperature.

Table 1 shows the manufacturing specifications of the PV module



Maximum power (Pmax)	[W]	215
Max. power voltage (Vpm)	[V]	42.0
Max. power current (Ipm)	[A]	5.13
Open circuit voltage (Voc)	[V]	51.6
Short circuit current (Isc)	[A]	5.61
Warranted minimum power (Pmin)	[W]	204.25
Output tolerance	[%]	+10/-5
Maximum system voltage	[Vdc]	1000
Temperature coefficient of Pmax	[%/°C]	-0.30
Voc	[V/°C]	-0.129
Isc	[mA/°C]	1.68

Note 1: Standard test conditions: Air mass 1.5, Irradiance = 1000W/m², Cell temperature = 25°C

Note 2: The values in the above table are nominal.

Warranty

Power output: 20 years (80% of minimum output power)

Product workmanship: 2 years

(Based on contract terms.)

$$\text{Efficiency} = \frac{\textit{maximum electricty power}}{\textit{incident illumination power}} \quad \textbf{at (STD)} \qquad \textbf{(5)}$$

Example

Determine the parameters of a module formed by 34 solar cells in series, under the operating conditions G=700 W/m^2, and Ta=34oC. The manufacturers values under standard conditions are: Isc = 3A; Voc = 20.4V; Pmax = 45.9 W; NOCT = 43^{o}C.

Solution:

1. Short-circuit current

Isc (700 W/m2) =3 x 0.7 = 2.1 A.

2. Solar cell temperature

Tc = 34 + 0.7 x (43-20)/80 = 54.12oC

3. Open-circuit voltage

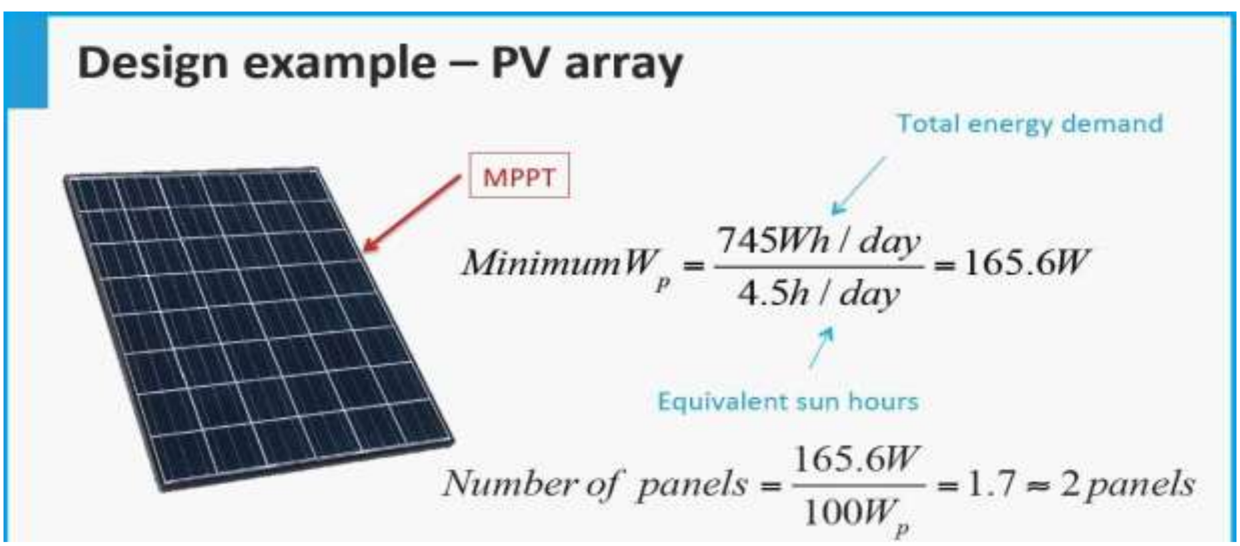
Voc (54.12oC) = 20.4 – 0.0023 x 34 x (54.12 – 25) = 18.1 V

4. Maximum power point

FF= 45.9/ (3 x 20.4) = 0.75

Pmax (G, Tc) = 2.1 x 18.1 x 0.75 = 28.5 W

Thus, noting the manufacturer's value of Pmax we see that the module will operate at about 62% of its nominal rating.



Electrical Data

Maximum Power at STC*	100 W
Optimum Operating Voltage (V_{mp})	18.9 V
Optimum Operating Current (I_{mp})	5.29 A
Open Circuit Voltage (V_{oc})	22.5 V
Short Circuit Voltage (I_{sc})	5.75 A
Module Efficiency	15.47%
Maximum System Voltage	600 VDC UL
Maximum Series Fuse Rating	15 A

Thermal Characteristics

Operating Module Temperature	-40ºC to +80ºC
Nominal Operating Cell Temerature (NOCT)	47±2ºC
Temperature Coefficient of Pmax	-0.44%/ºC
Temperature Coefficient of Voc	-0.30%/ºC
Temperature Coefficient of Isc	0.04%/ºC

Home Work

Determine the annual module power output of a SANYO (HIP-215NHE5) module in Baghdad, if the monthly average global radiation and ambient temperature are in below:

Month	Monthly average global radiation (kW h/m^2/day) (6 a.m. – 6 p.m.)	Monthly average ambient temperature (^{o}C) (6 a.m. – 6 p.m.)
Jan.	3.0	8.4
Feb.	3.8	14.7
Mar.	4.8	23.6
Apr.	5.7	28.0
May.	6.5	32.0
Jun.	7.3	36.6
Jul.	7.2	38.0
Aug.	6.6	40.0
Sep.	5.7	35.5
Oct.	4.4	27.3
Nov.	3.3	19.6
Dec.	2.7	13.4

6. PV Arrays

A PV array is a group of modules that are electrically connected either in series or in parallel. The electrical characteristics of the array are analogous to those of individual modules, with the power, current, and voltage modified according to the number of modules connected in series or parallel.

1. Increasing Voltage

PV modules are connected in series to obtain higher output voltages. Output voltage, *Vo,* of modules connected in series is given by the sum of the voltages generated by each module:

$$Vo = V1 + V2 + V3 + \dots \qquad (6)$$

An easy way to understand the concept of series-connected systems is through the analogy between a hydraulic system and an electrical system shown in Figure 6.5. As can be observed in the hydraulic system (left side), the water that falls from four times the 12 m height produces four times the pressure of water falling from the first level. This is analogous to the 48 V that the electrical system (right side) reaches after passing a current of 2 A through four modules connected in series. The current can be compared to the flow because both remain constant within their respective circuits, and the voltage is analogous to the role of pressure in the hydraulic system. Figure 6.6 provides an example of modules connected in parallel. The positions of blocking and bypass diodes are also shown. Diode sizes should by determined taking into consideration the maximum current generated by the PV array under short-circuit conditions. The electrical code stipulation used internationally requires that the current value supported by the diode should be at least 1.56 times the short-circuit current value of the array. Finally, the nominal power of the array is the sum of the nominal-power values of each module, irrespective of how the modules are wired in series or in parallel.

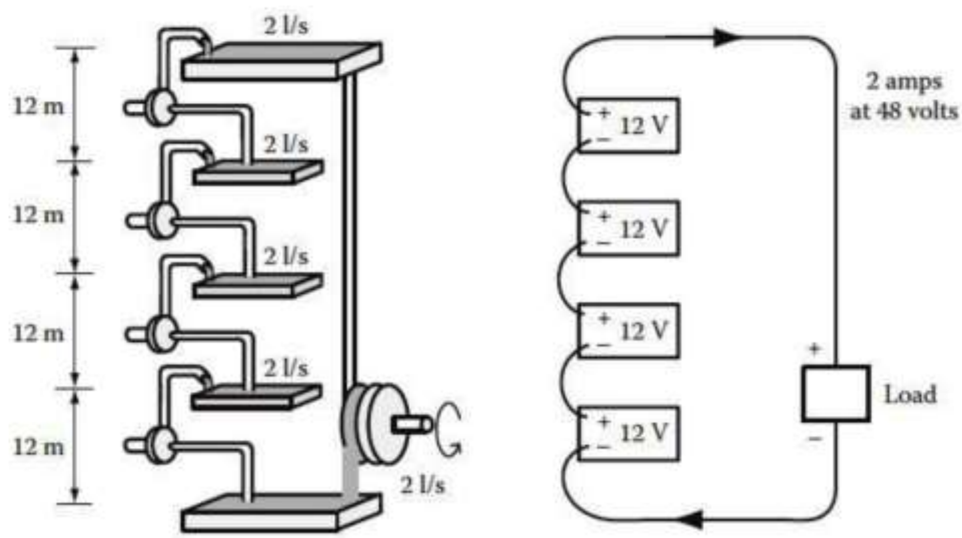


Fig.6.5 a analogy of a series connection using a hydraulic system and an electrical system

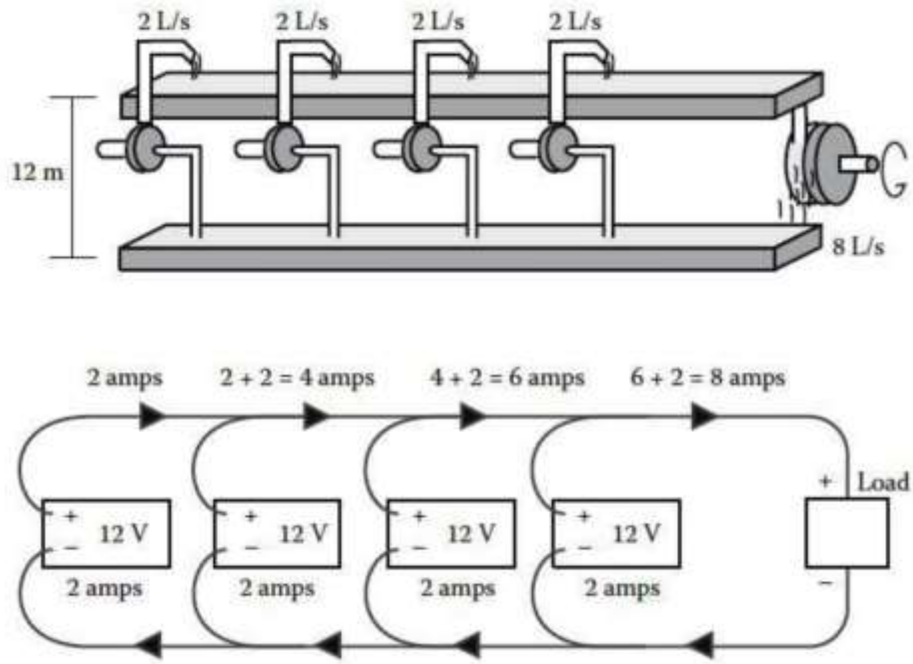


Fig. 6.6 hydraulic analogy of a parallel electrical connection, which is analogous to increasing flow of elections

7. PV-integrated Systems

- cooling PV improves efficiency
- heat can be used
  - in summer (hot water)
  - in winter (space heating) 1-

PV Integrated with Air Collector

2- PV/T Water Heating

Example: calculate the required number of PV module for power plant to add 4Mw generation capacity to the electric grid under Baghdad weather conditions (average daily global radiation is 5000 Wh/m^2 and average ambient temperature is 23^o C) . The specification of a PV module under the STD are :

Cell type	Polycrystalline silicon solar cell, 125.5 mm2
Number of cell	72 in series
Maximum power	157 W
Short circuit current	5.37 A
Maximum power point current	4.83 A
Open circuit voltage	43.1 V
Maximum power point voltage	34.6 V
Normal operating cell temperature	43 ^{o}C

. **Example: A house has the following electrical appliance usage:**

- **One 18 Watt fluorescent lamp with electronic ballast used 4 hours per day.**
- **One 60 Watt fan used for 2 hours per day.**
- **One 75 Watt refrigerator that runs 24 hours per day with compressor run 12 hours and off 12 hours.**

The system will be powered by 12 Vdc, 110 Wp PV module.

Determine power consumption demands

Total appliance use = (18 W x 4 hours) + (60 W x 2 hours) + (75 W x 24 x 0.5 hours)
= 1,092 Wh/day
Total PV panels energy needed = 1,092 x 1.3
= 1,419.6 Wh/day.

2. Size the PV panel

2.1 Total Wp of PV panel capacity needed = 1,419.6 / 3.4
= 413.9 Wp
2.2 Number of PV panels needed = 413.9 / 110
= 3.76 modules

Actual requirement = 4 modules
So this system should be powered by at least 4 modules of 110 Wp PV module.

3. Inverter sizing
Total Watt of all appliances = 18 + 60 + 75 = 153 W
For safety, the inverter should be considered 25-30% bigger size.
The inverter size should be about 190 W or greater.

4. Battery sizing
Total appliances use = (18 W x 4 hours) + (60 W x 2 hours) + (75 W x 12 hours)
Nominal battery voltage = 12 V
Days of autonomy = 3 days

$$\text{Battery capacity} = \frac{[(18\text{ W x 4 hours}) + (60\text{ W x 2 hours}) + (75\text{ W x 12 hours})]}{(0.85 \times 0.6 \times 12)} \times 3$$

Total Ampere-hours required 535.29 Ah

So the battery should be rated 12 V 600 Ah for 3 day autonomy.

5. Solar charge controller sizing

PV module specification

Pm = 110 Wp

Vm = 16.7 Vdc

Im = 6.6 A Voc =

20.7 A Isc = 7.5 A

Solar charge controller rating = (4 strings x 7.5 A) x 1.3 = 39 A

So the solar charge controller should be rated 40 A at 12 V or greater.

Do You Have Any Questions?