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DESIGN CONSIDERATIONS FOR STAND-ALONE PHOTOVOLTAIC (PV) CELL APPLICATIONS

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Abstract

Solar energy is one of the most important renewable energy sources. The photovoltaic (PV) cell systems are used to convert solar energy into electricity. PV systems are divided into two as fixed systems and tracking systems. Fixed systems are mounted at a certain tilt with horizontal to make full use of sunlight. The tilt angle of PV arrays in a fixed system depends on the location and time. If this tilt angle is determined well, the amount of insolation and the energy that is generated increases. When a stand-alone PV cell system is being chosen, certain design operations should be implemented. The number of modules and batteries needed for any system should be calculated by means of the amount of load, insolation level, module characteristics, etc. The design of system is finalized according to the energy demand.

Keywords: PV system design, tilt angle, solar energy.

Nomenclature

PV	photovoltaic	W	unit of power, watt (W)
kW	kilo watt	MW	mega watt
q	electron electric charge, $1.6*10^{-19}$coulomb	Wh	watt hours
G_{SC}	solar constant, 1367 W/m^2	WRC	World Radiation Center
NOCT	Nominal Operation Cell Temperature	T	temperature, Kelvin (°K)
V	voltage, volt (V)	I	current, ampere (A)
I_o	reverse saturation current, ampere(A)	I_l	component of the PV cell current
k	Boltzman's constant, $1.38*10^{-23}$ j/atom°K	STC	Standard Test Condition
V_{oc}	open-circuit voltage of cell	I_{SC}	short-circuit current of cell
G	ambient irradiation	G_o	reference ambient irradiation
V_m	value of module's maximum voltage, volt(V)	AM1.5	air-mass for STC
$E_{(T)}$	required daily energy, (Wh)	$E_{(M)}$	energy of a PV module, (Wh)
$E_{(B)}$	total usable capacity needed at 12V, (Ah)	n	day of year
E	east	N	north
$N_{(M)}$	number of module	$N_{(B)}$	number of battery

Greek symbols

Ø	latitude, (the angular location north or south of equator, °)
β	tilt angle, (°)
δ	declination angle, (°)

1. Introduction

The sun is a gaseous matter, with a mass of about 2.10^{30} kg, and a diameter of $1.39*10^9$ m. The distance from the sun to earth is about $1.49*10^{11}$ m [2]. The energy which is obtained from the sun per unit time is called the solar constant and is represented with G_{SC}. The value of the solar constant as adopted by the World Radiation Center (WRC) is 1367 W/m^2 (1.96 cal/cm^2 min or 4.92 Mj/m^2 hour) [1].

Solar, wind, biomass, wave, etc. are some of the renewable energy sources. Solar, wind and hydro are more commonly used than others. Solar energy has many advantages such as abundance, renewability, continuation, and pollution free etc. A square meter on earth's surface normal to the sun can receive as much as 1kW of solar radiative power approximately [2]. Solar energy is utilized both electricity and thermal energy. Photovoltaic (PV) cells are used to convert sunlight into electricity.

Since the power obtained from a single PV cell is low, PV cells are connected in series to form PV modules. If higher currents and voltages are required, PV arrays are formed by connecting modules. In order to obtain maximum output from a solar array and ensure that it has maximum insolation, the relationship between tilt and azimuth angle needs to be examined. When the daily output of an array on the roof of a house and the daily need for load are similar, solar energy is used more efficiently. Therefore, the tilt and azimuth angle on a solar array system cannot be chosen randomly. The array needs to be positioned at the right tilt and/or azimuth angle to give sufficient output [12, 15].

In some PV systems, motion of the sun is wanted to be tracked in a day. The purpose of these systems is to increase the system's efficiency. Therefore, two different systems which were the fixed and the tracking system were established for applications of the stand-alone PV system [5, 13].

The sizing of any PV system is important for design. Mellit et al.][7,8] has used artificial neural network (ANN) architecture for estimating of the sizing coefficients of PV systems based on the synthetic and measured solar radiation data. However, there are lots of different studies associated with the sizing of stand-alone PV systems [4, 6, 10, 14].

In this study, design processes were carried out for sizing of PV system. So, a PV-powered house was chosen as a design model. Design processes were operated step by step and the requirements of system were calculated. The Matlab software program was used for the calculation stages in the system.

Figure 1 shows the I-V characteristics of a typical cell [9]. The amount of the current and the voltage changes depending on the amount of sunlight shining on the cell. Then, the I-V equation is:

$$I = I_l - I_o(e^{(qV)/(kT)} - 1) \qquad (1)$$

where Io; is the diode reverse saturation current, Il; is the component of the PV cell current due to photons, electrical load ($q=1.6*10^{-19}$ coulomb), $k=1.38*10^{-23}$ j/K (Boltzman constant) and T is the cell temperature in Kelvin.

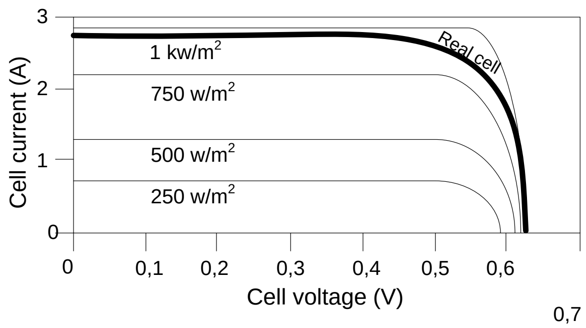


Fig. 1- I-V characteristics of the real and ideal PV cells under different illumination levels

Figure 1 shows that a PV cell has a voltage and current limitation. This indicates that the cell will not be damaged by open or short circuits. To identify a PV cell's short circuit current, V=0 is written. Then, $I_{sc}= I_l$. Thus, if the cell current is known under Standard Test Conditions (STC); that is for Go= 1 kW/m^2 and AM1.5, then the cell current in any other G radiation is calculated by:

$$I_{l\,(G)} = (G/G_o)*I_{l\,(Go)} \qquad (2)$$

In order to identify the cell's open circuit voltage, the cell current is set to zero and the equation in 1 is solved for Voc and the result is:

$$V_{oc} = \left(\frac{kT}{q}\right) * \ln\left(\frac{I_l + I_o}{I_o}\right) \approx \left(\frac{kT}{q}\right) * \ln\left(\frac{I_l}{I_o}\right) \quad (\text{because } I_l >> I_o) \qquad (3)$$

While the short circuit current of the cell varies in direct proportion with the amount of illumination, open circuit voltage is only logarithmically dependent on illumination.

2. Design stages and algorithm

PV cells are an important way of generating electrical energy. The energy produced by the cells goes through a PV cell system to reach the user. This system includes elements such as batteries, charge regulator or controller and loads. For example, cottages away from a city grid or communications stations may prefer to use these systems. The use of solar energy is particularly economical in places far away from a city grid as the maintenance costs are minimal; PV cells have a long-life, and produce clean and renewable energy. The loads can be DC or AC. If AC load is used, it needs to be added an inverter to the system. The sizing steps of a PV cell system are shown in Figure 2 [11].

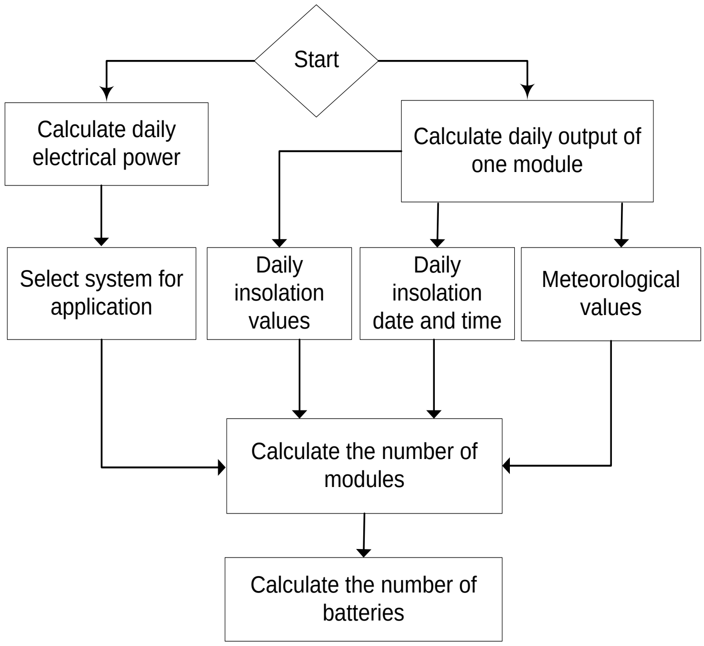


Fig. 2- Sizing of a PV cell system

For the design presented here, a PV-powered house will be used as a model. The stages of the design must be implemented in the order shown here. For the successful design of PV cell systems, the elements to be used and the technical characteristics of these elements need to be known. Therefore the design of a PV cell system is generally done step by step. The first step is to identify the daily electrical energy needed for each load. The power of each appliance and its daily using time needs to be known as well. The second stage is to calculate how much energy will be produced by a module. This calculation is made using the module's output current amount and the duration of insolation during the day. The third stage is the sizing of the solar arrays. This depends on the number of days that the storage will be needed (cloudy, overcast days) and the daily amount of energy needed. In order to determine a home's daily energy consumption (Wh), the power of each load and duration of use throughout the day needs to be known. Then, the required daily energy is [11]:

$E_{T(Wh)}$=Power of appliances (W)*Daily using time of appliance (hours per day,h) (4)

Solar arrays are exposed to different amounts of insolation depending on when and where they are used. As the angle of sunlight changes, so do the array's power levels. This is because an array's output is in direct proportion to the light that shines on it. The daily energy production of a module is calculated by using the insolation and module current values. The daily energy produced by a 12 V module is:

EM(Wh)=Effective array current(A)*Daily insolation (peak-sun hr per day, h) *12 (V) (5)

As the amount of insolation varies depending on geographical location and the time of day, the model needs using of meteorological data related to the region. The region chosen for this particular design was Elazig city, located in the west of Eastern Anatolia region in Turkey. Elazig lies on 39˚14'(E) longitude and 38˚40'(N) latitude, at an altitude of 989.753 meters above sea level [16].

The meteorological data regarding insolation in the last 6 years (2002-2007) is given in Table I [16]. These data comprises monthly averages in the last 6 years, which were used in the calculations.

Table I: The average values related to the amount of insolation for Elazig between 2002-2007 years

Values	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*Jun.*	*Jul.*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*
Average of insolation level (Wh/m^2 per day)	1750.51	2598.14	3693.39	4471.01	5834.58	6850.28	6668.37	5898.08	4948.68	3364.02	2241.55	1711.66
Duration of insolation (hours per day)	2.98	3.91	5.78	6.48	9.73	11.91	12.51	11.71	10.43	7.13	5.16	3.43

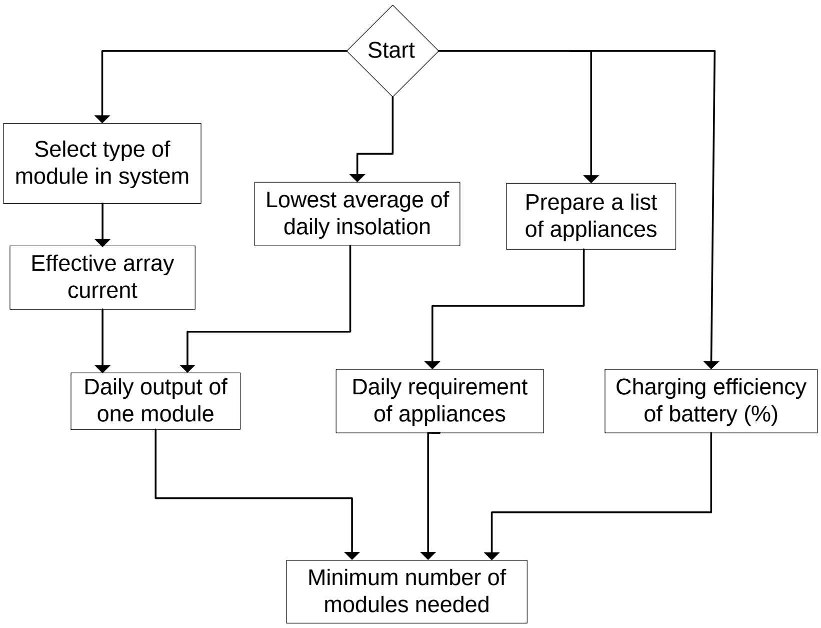
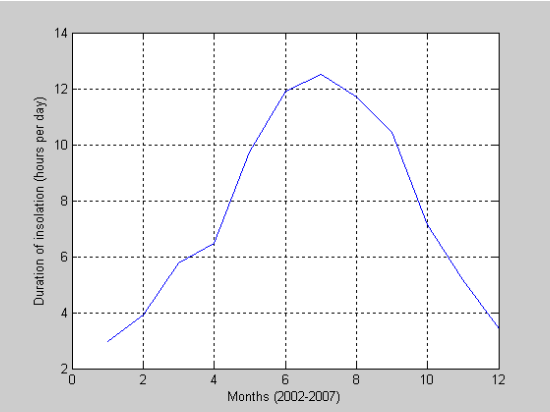
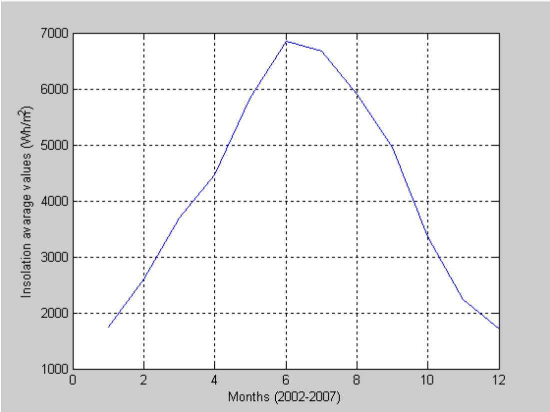


Fig. 3- Calculating the minimum number of modules in a PV cell system

Figure 3 shows the stages in calculating the minimum number of modules needed in a PV cell system [11]. The first stage is to identify the type of module needed. Catalogue values of this module and the amount of energy it can produce (Wh) is calculated by using meteorological data.

Then, the daily need for energy is determined according to the power in the system. The energy obtained is stored in the cells to be used at night or on overcast days. In this case, the charge efficiency of the cell also affects the system. With the help of this data, the number of modules needed for the system is calculated.





(a) **(b)**

Fig. 4- The graphical variation of the insolation time and values in Elazig between 2002-2007 according to months

Figure 4 (a, b) shows the monthly changes in the average insolation times and values in Elazig in the last 6 years. As shown in Table I and Figure 4, Elazig has highly favorable values as regards insolation about 6-7 months of the year.

In most PV cell systems, the energy stored during the day is used at night. During this process, the battery is still being charged and discharged. During the charge / discharge process, some losses occur and the charge efficiency depends on the battery. In lead-acid batteries, efficiency is about around 80% whereas, in nickel-cadmium batteries, it is around 70%. Accordingly, the minimum number of modules that are needed in the system is [11]:

NM=(Daily requirement of appliances,(Wh per day)) / Charging efficiency of battery (%)) / (Daily output of one module,(Wh per day at 12V)) (6)

Taking the data into account, step by step procedures are followed. The battery capacity needed is;

$E_{(B)(Total\ capacity,\ Ah\ at\ 12V)}$=((Daily requirement of appliances,(Wh per day)*Period of storage required, (days)) / 12V (7)

The discharge depth ratio and the Ah value at 12 V are added to these procedures and the required minimum number of batteries is calculated:

N(B)=(Total capacity,(Ah at 12V)/Maximum depth of cycles (%)) / (Full capacity specified for one 12V battery, Ah) (8)

These calculations are made to meet the daily energy need. If there are more cloudy or rainy days in the region than expected, then the number of days when the batteries is needed will increase. Therefore the number of days is used in the calculations.

3. The tilt angle of the array (β)

PV cell systems can be used in either a fixed or a tracking system. The tracking systems follow the movement of the sun throughout the day and thus try to utilize maximum of daylight. The fixed systems, on the other hand, are installed at a certain tilt angle which varies depending on the geographical location and time of day. The tracking systems are classified into two groups: a single axis and two axes. The rotation motion in practice is usually horizontal east-west, horizontal north-south, vertical, or parallel to the earth's axis. For a plane rotated about a horizontal east-west axis with a single daily adjustment so that beam radiation is normal to the surface at noon each day [1],

$$\cos\theta = \sin 2\delta + \cos 2\delta * \cos\omega \quad (9)$$

where, θ represents angle of incidence, which is the angle between the beam radiation on a surface and the normal to that surface, ω represents hour angle which is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15º per hour. In any fixed PV cell system, the tilt angle is determined so that light shines directly on the array, perpendicular to its surface. In the Northern hemisphere, arrays face south with a tilt angle between 0º≤β ≤180º. For a fixed array to make use of maximum daylight at noon, the tilt angle should be [1]:

$$\beta = | Ø-\delta | \quad (10)$$

Ø; here represents the latitude angle formed in the north or south of the Equator to its center. The north of the Equator is considered positive, and the south negative. The latitude angle changes between -90º≤Ø ≤90º. δ is the declination angle and represents the angle between the Sun's direction and the Equator, -23.45°≤ δ≤23.45°. The degree of declination angle is calculated according to the following equation [3]:

$$\delta = 23.45 * \sin\left[\frac{(360 * (284 + n))}{365}\right] \quad (11)$$

Here, n refers to the day of the year and, when January 1 is the starting point, n=1.

To ensure optimum performance on a given day, a fixed array system needs to be Ø-δ, as mounted from horizontal with an angle of shown in Figure 5.

This ensures that sunlight at noon is perpendicular to the plane of the array. The tilt angle of the PV cell system may be (Ø-15)° on average for maximum summer performance, and (Ø+15)° on average for maximum winter performance. For optimal spring or autumn performance, or for annual performance, the plane needs to be mounted with the approximate angle of (0.9*Ø) ° [9].

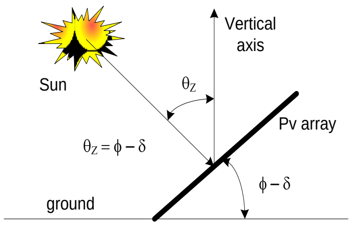


Fig. 5- Optimum tilt angle of a fixed PV array

3.1. A Model Design: Home Model

The model chosen was a PV-powered house in Elazig. A stand-alone PV cell system is used in this home. The loads with different power and working times are fed by this system. The loads are DC and their power and working times are given in Table II. If calculations are made for the values given in Table II, the daily need for energy is:

$E_{T(wh)}$=160+180+120+300+240+40+200+400+20=1660 Wh

Using this data, the number of modules necessary can be calculated.

Table II: The powers of daily electrical loads to be used in houses and their usage durations

Appliances	*Power (W)*	*Duration per day (hours-h)*	*Amount of energy per day (Wh / day)*
2 * 20 W fluorescent	40	4	160
2 *15 W lighting	30	6	180
Bedroom fan	40	3	120
Kettle	600	0.5	300
TV	80	3	240
Cassette-player	20	2	40

Appliances	*Power (W)*	*Duration per day (hours-h)*	*Amount of energy per day (Wh / day)*
Iron	800	0.25	200
Refrigerator	100	4	400
Small electronic device	10	2	20
Total	**-**	**-**	**1660**

The energy produced by the module is stored in the batteries to be used at night or on overcast days. If the efficiency of the battery is 80% and its discharge depth is 70%, the number of modules needed and the daily energy requirement is:

$$E_{T\ (wh)} = (1660 / 0.8) = 2075 \text{ Wh and}$$

$$N_M = 2075 / 131.71 = 15.75$$

Therefore the minimum number of modules that are needed is 16. If the system voltage is 24 V instead of 12 V, 16 modules are needed because 16 is the nearest even number above 15.75. Thus, 16 (12 V, 3.2 A) modules are connected in parallel. Suppose that the number of overcast days when the battery is needed is 3:

$$E_{(B)} = (1660*3) / 12 = 415 \text{ Ah}$$

When the discharge depth of the battery is considered:

$$415 / 0.7 = 592.857 \text{ Ah}$$

If the total capacity value of the battery is 100 Ah:

$$N_{(B)} = 592.857 / 100 = 5.92$$

Therefore the minimum number of batteries that are needed is 6. If the system voltage is 24V instead of 12V, 6 batteries (12V, 100Ah) are needed.

To compute these calculations and materialize the design procedures given above, Matlab software program were used. The program should be prepared and written in line with the algorithm, and then all calculations should be made step by step as shown in the sample model here.

4. Conclusions

As the conventional sources of energy on the Earth become consumed, studies on alternative energy sources have become increasingly important. Solar energy plays a critical role among alternative/renewable energy sources as it is a promising, pollution free, safe and strategically sound alternative to current methods of energy generation. Owing to these advantages, solar energy is currently being used for heating and cooling buildings, traffic signalization, agriculture, space shuttles, communications systems, and electricity production. Producing electrical energy from solar energy allows us to make better use of existing conventional energy sources. In order to reduce the problems that appear as a result of global warming, the use of solar energy should be made more accessible and common. Countries around the world have different levels of insolation due to their different geographical locations. If insolation is used most efficiently, solar energy can be a viable alternative and national economies will benefit from this.

Solar energy is one of the most important alternatives in meeting the energy needs of the future, and it must be considered for electrical energy production.

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