O 118. DIMENSIONING AND ECONOMIC ANALYSIS OF A GRID-INDEPENDENT PV SYSTEM FOR A STANDARD HOUSING

Kıvanç Başaran[1], Elif Merve Bahar[2], Menal İlhan[3], İsa Serdar Topbaş[4]

[1]*Manisa Celal Bayar Üniversitesi,Enerji Sistemleri Müh.*
[2]*Manisa Celal Bayar Üniversitesi, Fen Bilimleri Enstitüsü,Enerji Sistemleri Müh.*
[3]*Manisa Celal Bayar Üniversitesi,Enerji Sistemleri Müh.*
[4]*Manisa Celal Bayar Üniversitesi,Enerji Sistemleri Müh.*

E-mail: kivanc.basaran@cbu.edu.tr, elif.kalyoncu@cbu.edu.tr, menal.ilhan@cbu.edu.tr, serdar.topbas@cbu.edu.tr

ABSTRACT: With the increasing population and industrialization, the need for electrical energy is increasing day by day. In order to meet the need, the use of renewable energy sources has come to the forefront especially in recent years. Among the renewable energy sources, solar energy technologies are the most appropriate solution to meet the individual energy needs. Photovoltaic (PV) systems that convert solar energy into electrical energy are separated as grid-dependent and grid-independent according to their connection type. Grid-independent PV systems are preferred when there is no network, frequent and long-term disconnection of the network, the transmission lines are not economical.

In this study, economic analysis and dimensioning of the grid-independent photovoltaic system were conducted for a standard housing in the Turgutlu district of Manisa province. The analyses were performed in the Renewable Energy Laboratory supported by the MCBU BAP Unit.

Life cycle cost (LCC), annual life cycle cost (ALCC), electricity cost (UCel) of the components used in this system were calculated. This model can be used to design and assess the economic feasibility of off-grid PV electrification in any geographical location of the world by sorting input data viz. solar insolation, cost of the conventional energy as well as the market prices of the off-grid PV components.

Keywords: Photovoltaic (PV) systems, grid-independent systems, economic analysis

1. INTRODUCTION

The main reasons such as the increasing need for energy and the harm to the environment of fossil fuels used in energy production led to the search for alternative sources in production. In recent years, the trend towards the use of renewable energy sources has increased.

Renewable energy is the energy that is assumed to be practically unlimited, which can be used continuously and repeatedly. Solar energy, wind energy, geothermal energy from the earth, biomass produced from plants and hydropower obtained from water are also considered in the renewable energy group (Kıyga, 2013).

Renewable energy technologies enable us to convert energy, which naturally exists in the world without human contribution, into a form of usable energy. The energy carried by the sun's rays, the energy of the wind, the heat of the earth and the nucleus of the earth, the plants' energies, and many other known and unknown forms of energy are transformed into forms of energy that can be used to achieve higher comfort and higher standards of life quality (Baş, 2016).

Solar energy, which is one of the renewable energy sources, is preferred because it is clean and does not harm the environment. Systems that generate electricity from solar energy are called photovoltaic systems. The operation and maintenance and repair costs of these systems are lower than systems that provide the generation of energy from other energy sources (Özgöçmen, 2007).

Photovoltaic systems according to connection types; they can work on the network or independent of the network. Many literature studies have been conducted on network independent systems.

In grid-independent systems, Mandeli et al. (2016) studied the effect of load profile on the design of the photovoltaic system on system sizing. In the sizing of the system; energy needs, daily load profile, photovoltaic and battery system showed that the economic analysis is important. Gallegos et al. (2018)

studied the sizing and placement of the photovoltaic system in diesel generator systems. In their studies, they aimed to reduce environmental pollution and to improve the economy. As a result of the study, they observed that installing the system in remote locations is cost effective and reduces the emissions that cause environmental pollution.

On the energy management of the system, Baurzhan et al. (2016) conducted studies on the African continent. By reviewing the feasibility of network-independent systems, five different main issues have been focused on in terms of falling system costs: cost effectiveness, affordability, financing, environmental impact and poverty reduction. In their study, Goldsworthy and Sethuvenkatraman 2018 used the electricity consumption profiles of the houses consumed from the grid for the analysis of the grid-independent photovoltaic system. Residents who want to leave the grid can make fundamental changes in their consumption patterns to minimize the size of the photovoltaic - battery system. As a result, it has been shown that especially hot water and air conditioning settings can increase the economy significantly, and even device efficiency improvements reduce electricity costs.

In the studies on the batteries used in the system, Bogno et al. (2017) conducted a detailed analysis based on the test results of the battery charge control which ensures the long life and high safety of the storage and production systems. As a result of their experimental work, they charged the 24 V-55 Ah battery with a 175 kW photovoltaic module. Ayengo et al. (2018) compared photovoltaic systems using lithium nickel cobalt aluminum oxide and lead-acid batteries. Models were developed in Matlab / Simulink application and solar radiation, temperature values and electrical charge data of Dodoma city, Tanzania capital were used. The electricity costs for both battery systems were compared and lithium nickel cobalt aluminum oxide batteries were found to be less costly than lead-acid batteries.

In this study, for the design of the grid independent photovoltaic system, the load in a residence in Turgutlu district of Manisa and the solar radiation values of that region were taken into consideration. The system is designed by finding the number of photovoltaic panels, battery and inverter capacities used in the system to be designed. Life cycle cost (LCC), annual life cycle cost (ALCC), electricity cost (UC_{el}) of the components used in this system were calculated. The analyses were performed in the Renewable Energy Laboratory supported by the MCBU BAP Unit.

2. REQUEST FOR ENERGY FOR HOUSING

In order to calculate the energy demand, firstly the highest electrical load of this house must find out. The electrical charge requirement (L_{el}) in this housing is shown in Table 1. The average daily demand for the selected house was calculated as 5.54 kWh/day.

Table 1. Electricity Load Calculation Required for Housing

Load profile					
Equipment in use	No. of equipments	Power of equipment	Total wattage (W)	Daily appliances use (h)	Daily energy required (kWh/d)
Lamps	9	23	207	3	0,62
Refrigerator	1	80	80	24	1,92
Washing machine	1	1000	1000	2	2
TV	1	180	180	4	0,72
Notebook	1	70	70	2	0,14
Total					5,4

3. ELEMENTS OF INDEPENDENT PHOTOVOLTAIC SYSTEM FROM THE GRID

In the photovoltaic system independent from the grid, there are panels, charge controller, battery and inverter. The block diagram of the photovoltaic system is shown in Figure 1. In the systems independent from the grid, the sunlight falling on the panels during the day generates electrical energy at the ends of the panels. Electrical energy is stored in the battery group with charge controllers and kept ready for use. In order to be used in devices operating with alternating current, direct current is converted to alternating current (220 V, 50 Hz sine wave) and transferred to the devices.

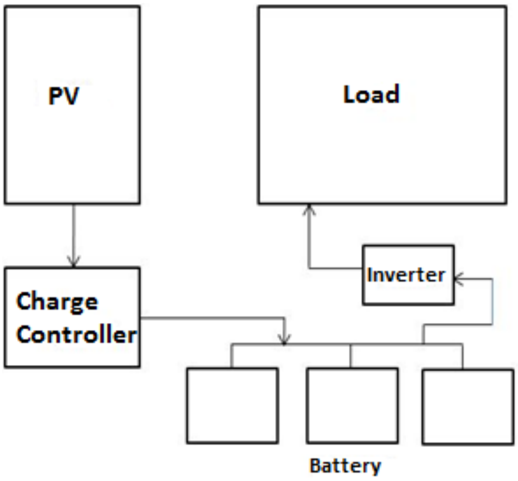

Figure 1. Layout of an off-grid PV system

4. DESIGN OF AN OFF-GRID PV SYSTEM

The design of the PV system starts with the known initial load and available solar energy per unit area. The average daily solar energy input (H_{avg}) over the year for Turgutlu is nearly 5.30 kW h/m^{2}d.

4.1. Sizing of the PV array

The size of the PV array can be calculated using Eq. (1)

$$A_{PV} = \frac{L_{el}}{H_{avg} * \eta_{PV} * \eta_B * \eta_I * T_{CF}} \tag{1}$$

where; A_{PV} is the required area of PV array in m^2, L_{el} is the required electric load in kWh/d, H_{avg} is the average irradiation available per day in kWh/m^{2}d, η_{PV} is the efficiency of PV panel in %, η_B is the battery efficiency in %, η_I is inverter efficiency in % and T_{CF} is the temperature correction factor normlly taken as 1,23 % per ^{o}C for crystalline silicon [48]. The battery and inverter efficiency is generally taken to be 85% and 97%, respectively.

The peak PV power ($P_{p(PV)}$) can be calculated using Eq. (2)

$$P_{P(PV)} = A_{PV} * I_P * \eta_{PV} \tag{2}$$

where; *Ip* is the peak solar irradiance taken as 1000 W/m2.

4.2. Sizing of the backup battery

The storage capacity of the battery (B_{SC}) is calculated based on the continuous number of cloudy days, battery efficiency, depth of discharge of the battery and efficiency of the inverter as shown in Eq. (3)

$$B_{SC} = \frac{N_{CCD} * L_{el}}{\eta_B * D_d * \eta_I} \tag{3}$$

where; N_{ccd} is the largest number of continuous cloudy days and D_d is maximum permissible depth of discharge of the battery.

4.3. Sizing of the charge controller

The battery charge controller is employed in PV system to safely charge the batteries and remove the risk of overcharging the batteries. This device also helps in maintaining the long life of the batteries. The charge controller should be selected carefully so that it must be able to carry short circuit current of the PV array.

4.4. Sizing of the inverter

The inverter is selected in such a way that it must be able to handle the maximum expected power of AC loads. Therefore, it must be selected atleast 20% higher than the total rated power of the required AC loads (Table 1).

5. SIZING RESULTS OF AN OFF-GRID PV SYSTEM

The area of PV for the required load is calculated to be 6,626 m^2 assuming efficiency of PV panels as 15,49%. The peak PV power calculated is 1026,32 Wp.
CSUN 300-72M PV module has been selected for stand-alone PV system. The module is made of 72 monocrystalline silican cells connected in series to provide peak power of 300 Wp. The characteristics and specifications of PV module are shown in Table 2.

Table 2. Characterisitcs of PV module

Characteristic	Rating	Unit
Maximum power, P_{max}	300	W
No. of cells	72	No.
Voltage at P_{max}, V_{mp}	36,1	V
Current at P_{max}, I_{mp}	8,32	A
Short circuit current (I_{SC})	8,80	A
Open circuit voltage (V_{OC})	44,8	V
Efficiency	15,49	%

A total number of 8 modules are required with a peak power of single module as 300 Wp, maximum voltage 36,1 V and maximum current as 8,32 A at STC of 1000 W/m^2 and 25 °C. The series and parallel configurations can be adjusted based on required DC bus voltage. The required capacity of the storage battery is calculated to be 1920 W h assuming N_c as 1 day and DOD as 80%. Based on DC bus voltage of 12 V, the required capacity of the battery is calculated to be 160 Ah.
A graph showing the average of each particular month and corresponding power produced from off-grid PV system is shown in Fig. 2. Fig. 2 depicts the average power produced during different months of the years. It is evident from the Figure that peak average value in July is maximum and in December is minimum. The reason is that the city of Manisa is lying in northern hemisphere having maximum solar insolation in summer than in winter season and the energy range vary from about 137 kWh in peak winter (Dec) to 456 kWh in peak summer (July). The total energy produced per annum from off-grid PV has been found to be 3485 kWh. The results have shown that the annual energy produced using off-grid PV system is much higher than the annual energy demand throughout the year justifying the appropriate size and design of the existing PV system for continuous power generation for household electrification.

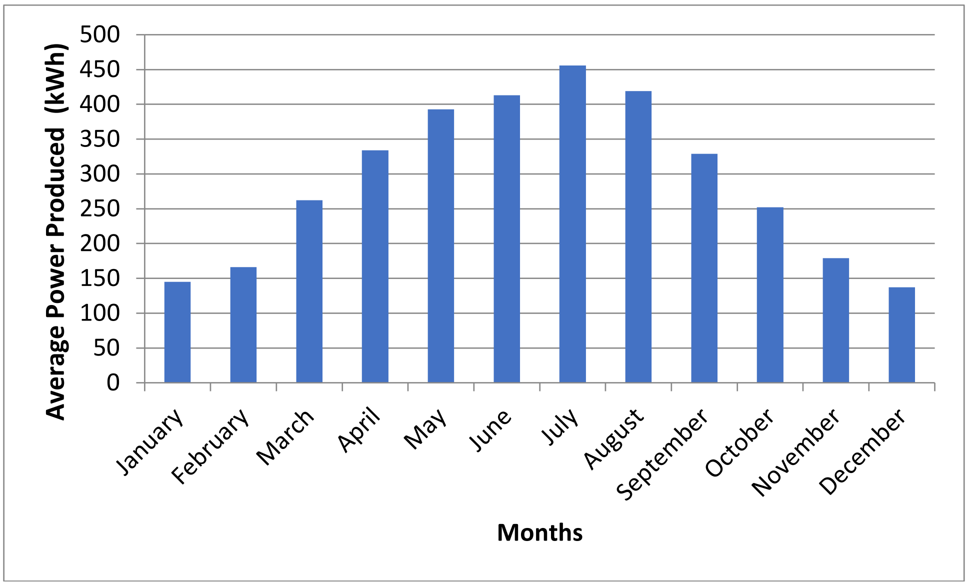

Figure 2. Average power produced from off-grid PV system

6. LIFE CYCLE COST ANALYSIS OF OFF-GRID PV SYSTEM

The life cycle cost analysis of off-grid PV system consists of total fixed and operating costs over its life expressed in today's money. The major cost of PV system includes acquisition costs, operating and maintenance cost. The total life cycle cost of PV system includes the sum of present worth (PW) of PV modules, storage batteries, charge controller, inverter, installation, and operation and maintenance cost. In case of PV system the life of system is considered to be 25 years except for storage batteries that is taken to be ten years. Therefore, each group of batteries needs to be replaced after every five years with effect of inflation (i) and discount rate (d).

The PWs of all the components can be calculated using the following procedure;
Cost of PV array,
C_{PV}=Unit cost of PV × No. of modules × Peak module power

Initial cost of batteries,
C_B=Unit cost of battery × battery size
The PW of 1st and 2nd group of batteries after 10 and 20 years can be calculated using Eq. (4).

$$C_{B1} = C_B * (\frac{1+i}{1+d})^N \tag{4}$$

The cost of charge controller is calculated using unit cost of charge controller multiplied by size of the charge controller and inverter cost as unit cost of the inverter multiplied by size of the inverter. The installation cost is considered to be 10% of initial cost of PV modules.

The PW of maintenance cost (C_m) can be calculated using annual maintenance (M) cost and lifetime of the system using Eq. (5).

$$C_M = M * \left(\frac{1+i}{1+d}\right) * \left(\frac{1-(\frac{1+i}{1+d})^N}{1-\left(\frac{1+i}{1+d}\right)}\right) \tag{5}$$

Finally, the LCC of the system can be calculated using Eq. (6).

$$LCC = C_{PV} + C_B + C_{B1} + C_{B2} + C_C + C_I + C_{inst} + C_M \tag{6}$$

The annualized LCC (ALCC) of off-grid PV system in terms of its present value can be calculated using Eq. (7).

$$ALCC = LCC * \left(\frac{1-(\frac{1+i}{1+d})}{1-(\frac{1+i}{1+d})^N}\right) \tag{7}$$

The unit electrical cost can be calculated using Eq. (8).

$$UC_{el} = \frac{ALCC}{365*L_{el}} \tag{8}$$

To calculate the cost of the suggested off-grid PV system, the following data of the system components have been taken into account using current market prices as shown in Table 3. The inflation and discount rate is taken to be 9% and 8%, respectively.

Table 3. Unit Costs Of PV System Components

Item	**Unit cost**	**Unit**
Cost of PV	0,48	$/W
Cost of battery	1,66	$/Ah
Cost of charge controller	1,319	$/A
Cost of inverter	0,413	$/W
Installation cost	10% of PV	$
Operation and maintenance cost	2% of PV cost	$

Using the above methodology and equations, the PW's of all the items have been calculated. The cost of PV array is calculated to be 1152 $. The PW's of initial set of batteries was calculated to be 266.323 $. The PWs of group of batteries for first after 10 years and second after 20 years were calculated to be 292,035 $ and 320,231 $ respectively. The total cost of charge controller and inverter was calculated to be 26,38 $ and 1733.935 $ respectively. The installation of PV system is taken as 10% of initial cost of PV system and was calculated to be 115,2 $. The PW's of maintenance cost (2% of initial PV cost) was calculated to be 650,754 $.
Finally, the total LCC of the system is the summation of all PW's of the system components including installation and maintenance cost and was calculated to be 4556,859 $. The Annualized Life Cycle Cost (ALCC) of the system was calculated to be 162, 83 $ per year. The unit electrical cost of the system was calculated to be 0,0806 $/kWh.

7. CONCLUSIONS

With the increasing population and industrialization as well as with the depleting resources of fossil fuels, the utilization of solar energy is gaining popularity worldwide for household electrification. It is imperative to enhance the acceptance rate of this technology, it is worth full to determine the proper design, feasibility, viability, financing indicators, and risk factors involved in the implementation of off-grid PV electrification system.
The present study focuses on the design aspects and economics analysis of an off-grid PV system to fulfil the required load for a residential house in Turgutlu. This paper covers the algorithm for sizing of the complete PV system to determine the required capacity of peak PV array, battery storage capacity, size of charge controller and inverter to meet the energy demand. As a result of mathematical modeling, the peak power and area of PV modules, capacity of battery backup, size of charge controller and inverter were determined to be 1026,32 Wp and 6,626 m2, 1920 W h, 20 A and 4200 W, respectively. In order to assess the economic feasibility of this system to the end-users, life cycle cost analysis of off-grid PV system under consideration has been carried out and was found to be 4556,859 $. Annualized life cycle cost and unit electricity cost have also been calculated to be 162,80 $ per year and 0,0806 $/kWh, respectively.
This model can be used to design and assess the economic feasibility of off-grid PV electrification in any geographical location of the world by sorting input data viz. solar insolation, cost of the conventional energy as well as the market prices of the off-grid PV components.
This study were performed in the Renewable Energy Laboratory supported by the MCBU BAP Unit.

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