International Journal of Scientific & Engineering Research, Volume 7, Issue 11, November-2016
ISSN 2229-5518

Simulated Performance of a Grid-Connected and Standalone Photovoltaic Power System

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Abstract - *This paper presents simulated performance of a 5.5kW grid-connected and 7 kW standalone photovoltaic (PV) power system. The grid-connected system was synchronized with the commercial grid and standalone system was modelled to supplylighting and fan load of a library building at the College of Science and Technology, Phuentsholing.The system was modeled in TRNSYS 17 and simulated with hourly climate data from SolarGIS. The simulated performance was then compared with outputs from HOMER model which used average monthly climate data from NASA. From the simulation, it was found energy yield is higher from TRNSYS simulation compared to the HOMER model. Similarly unit cost of energy is lower in case of TRNSYS simulation compared to the HOMER model.*

Index Terms-Bhutan, Cost of energy, Grid-connected, HOMER, SolarGIS, Standalone, *TRNSYS 17*

1 INTRODUCTION

Climate change and depletion of fossil fuels have become major issues worldwide. The root cause of both issues lies in the increasing use of fossil fuels in all sectors. Fossil fuels which are non-renewable resources are depleting much faster than being formed. Their combustion releases carbon dioxide and other greenhouse gases which contribute to climate change. One of the potential solutions to these issues is minimizing the use of fossil fuels by adopting renewable and energy efficienttechnologies.

Bhutan located between India and China has no proven deposits of fossil fuels but blessed with large hydropower potential. As of 2015, only 1488 MW of hydropower has been installed out of 16 GW techno-economically viable[1] in [2]. Currently, several hydropower plants are under construction with a total capacity of 2910 MW [3]. There are also plans to harness 20 MW power from various renewable energy sources by 2025 [4]. Bhutan has good potential for solar power plants as it receives good amount of solar irradiation as shown in Figure 1. Thus, realising the importance of renewable energy technology, the College of Science and Technology had installed 12.5 kW solar PV system (5.5 kW grid-connected and 7 kW standalone) with the financial support from GEF/SGP UNDP. College of Science and Technology is located at 26.85° North latitude and 89.39° East longitude. The installed solar PV power plant was designed using HOMER program [5]. HOMER is a Hybrid Optimization Model for Electric Renewable and is one of the simulation models developed by National Renewable Energy Laboratory USA [6]. It has many possible combination of renewable energy systems and simplifies the task of evaluating design options for both off-grid and grid-tied solar PV systems.The performance of the system was predicted using HOMER model [7]. The authors have reported the estimated cost of generation as US$ 0.08/kWh for grid-connected system and US$ 0.13/ kWh for standalone system. As there were no ground measured climate data, the authors used average monthly climate data extracted from NASA SurfaceMeteorology and Solar Energy (SSE) website[8] as input data. The authors have stated that the resultscould vary with the measured climate data [7] and their results should not be taken as a basis for project implementation. Therefore in this paper, the performance of the same system (5 kW grid-connected and 7 kW standalone) were estimated based on the TRNSYS simulation using hourly climate data from SolarGIS.

HOMER and TRSNSYS programs have been used in the past to investigate the performance of solar PV system. Solar PV based power system with battery storage was installed to supply a residential load located near Siliguri, West-Bengal, India. The system was modeled using HOMER program and analysed in two modes, grid-connected and standalone [9]. The cost of energy (COE) was estimated as $ 0.078/kWh in case of the grid-connected system and

$0.874/kWh for standalone system.A grid-connected PV was installedfor a residential house in Amman [10]. The system comprised of

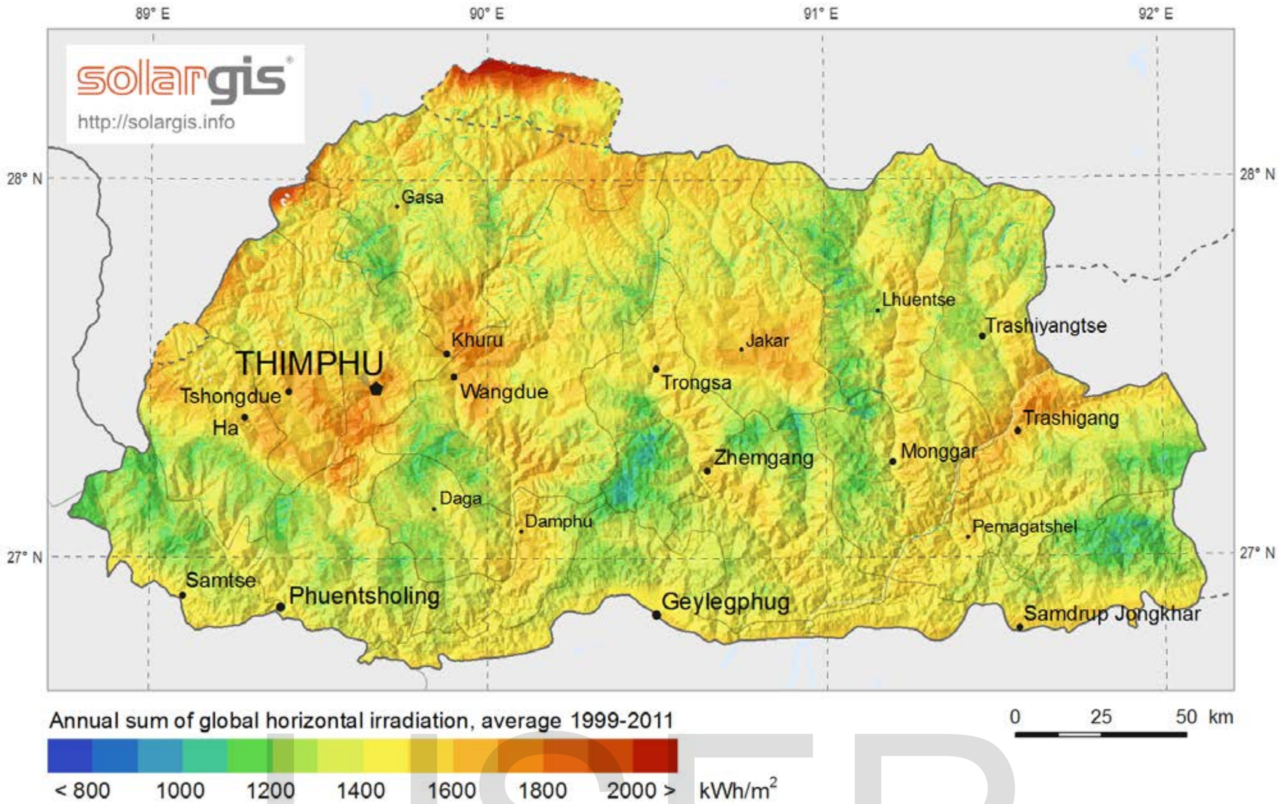

Fig.1. Annual global horizontal irradiation map of Bhutan (SolarGIS 2014)

2 kW grid-connected solar PV panels with a 2 kW inverter which was also simulated using HOMER with climatic data from NASA surface meteorology and Wind Energy Resource Assessment. The estimated COE was $ 0.228/kWh which was quite high compared to the conventional energy. Salam *et al.*[11]designed and analysed a standalone solar PV system to supply lighting load for Renewable Energy Lab in Sohar Oman. The system was modeled using HOMER. The simulation resultsshowed the solar PV system is an attractive option with energy cost of $0.561/kWh. Homer program was also used to design a 9 kW solar PV system to supply health clinic in Oman. For an average daily load of 24.31 kWh, the COE was found to be $0.418/kWhwhich is lower than the diesel generator operating cost of $0.558/kWh [12].The above studies indicate that HOMER has been used to design, model and optimize both grid-connected and standalone solar PV power plants. However, none of the authors reported validation of models using experimental results. Therefore, the validity of simulated performance using HOMER models cannot be ascertained and the study is inconclusive.

TRNSYS simulation of solar PV systems on the other hand has been validated by several authors in the past. Quesada *et al.* [13] modelled 7.2 kW grid-connected solar PV system in TRNSYS environment and was validated with the experimental results. The simulation results from TRNSYS were found to accurately predict long-term performance of the system. Kanyarusoke, Gryzagoridis and Oliver [14] concluded that within limits of climate data, TRNSYS modelling reliably predicted energy yields from the solar PV panels. TRNSYS simulation was also used to assess the performance of a 124.2 kW installed grid-connected solar PV system in the north of Portugal [15]. The results from TRNSYS simulation was compared to the measured output of the plant. The results showed that TRNSYS to be a good tool to predict the annual energy production of a solar PV plant.

Lovelace [16] found that TRNSYS simulation model is able to predict output energy reliabley compared to other programs. Similarlry, Balasubramani and Vijayakumar [17] modelled one kW grid-connected solar power plant in TRNSYS 17 environment.Mottillo [18] also observed that TRNSYS simulation results agreed well with the monitored data. Thus, it could be inferred from the above authors that TRNSYS program with accurate input climate data, can predict accurate results.

2 SYSTEM DESIGN and MODELING

2.1 Grid-connected System

The grid-connected solar PV system is synchronised with the commercial grid. It comprises of 22 panels of 250 Wp, 24 V which were configured 11 in series and 2 in parallel. Figure 2 shows block diagram of a 5.5 kW grid-connected solar PV system installed at the College of Science and Technology. The solar panels were flush mounted on the roof of the library building at 13° with azimuth of 15° South East.

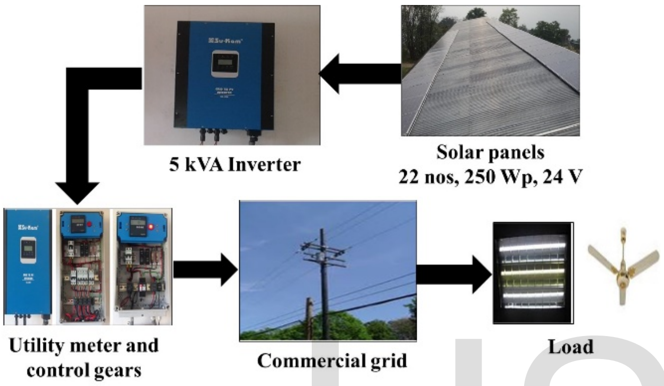

Fig.2. Block diagram of a grid-connected solar PV system

2.2 Standalone System

Standalone solar PV system is connected to 2.88 kW lighting and fan load of a reading room of the library building. It comprises of 28 panels of 250 Wp, 24 V configured 4 in series and 7 in parallel; 200 Ah, 12 V battery connected 8 in series and 2 in parallel. It was designed to supply 8 hours of uninterrupted power to the reading room. Figure 3 shows block diagram of a 7 kW standalone solar PV system installed at the College of Science and Technology. The panels were flush mounted on the roof at same slope and azimuth as that of the grid-connected system.

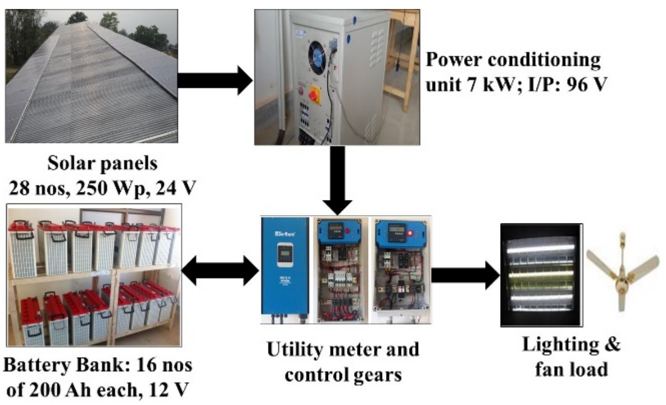

Fig.3.Block diagram of a standalone solar PV system

2.3 TRNSYS Model

Both the systems were modeled in TRNSYS program version 17.01.0028. TRNSYS is transient simulation program which is based on anopen modular structure approach. The source code of the kernel as well as the component models is delivered to the end users. Due to its modular approach, TRNSYS is flexible for modeling a variety of energy systems in differing levels of complexity. Supplied source code and documentation provide an easy method for users to modify or add components not in the standard library. Figure 4 and 5 shows TRNSYS model for grid-connected and standalone system respectively.

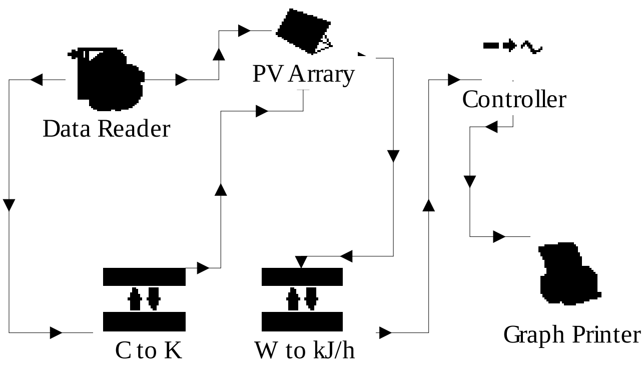

Fig.4. TRNSYS model of a grid-connected system

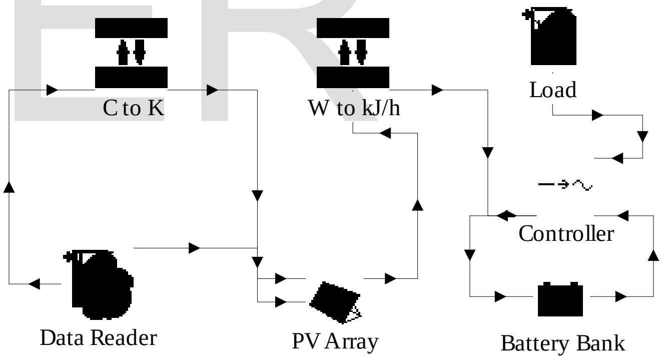

Fig. 5. TRNSYS model of a standalone system

3 CLIMATE DATA

In this paper long term average climate data from SolarGIS [19] was used to simulate the solar PV systems. As the results are to be compared with the outputs predicted by HOMER model which used input climate data from NASA, solar radiation data and ambient air temperature used in HOMER model are reproduced here. Figure 6 shows long term average monthly global horizontal irradiation for Phuentsholing. From the figure, it can be observed that solar irradiation data extracted from NASA is higher than data from SolarGIS. Not only there is difference in magnitude of solar irradiation, occurrence of maximum and minimum solar irradiation is different for two sets of data. The maximum solar irradiation received is 5.89 kWh/m²/day in

April in case of NASA data and 4.91 kWh/m²/day in May from SolarGIS.Similarly, the minimum solar irradiation received is 3.91 kWh/m²/day in July in case of NASA data and 3.33 kWh/m²/day in January from SolarGIS.

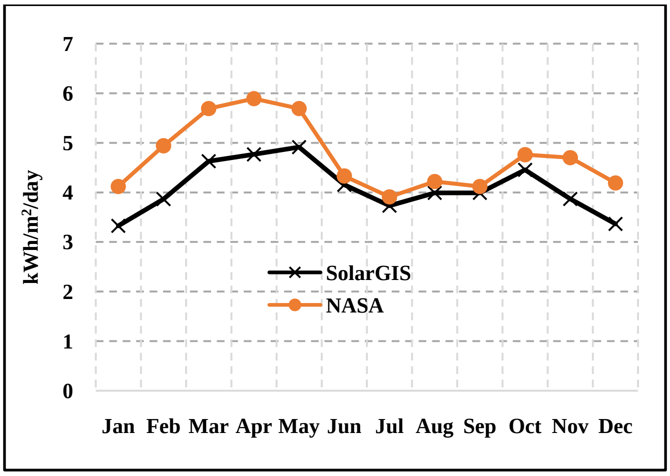

Fig. 6. Monthly long term average global horizontal irradiation

Solar PV output is also affected by the temperature of the particular place due to its effect on the solar PV panels. The long term average monthly ambient air temperature is shown in Figure 7. As in the case of solar irradiation, temperature data from NASA is higher than the data from SolarGIS. However, unlike solar irradiation, the maximum and minimum temperatures occur in same months.

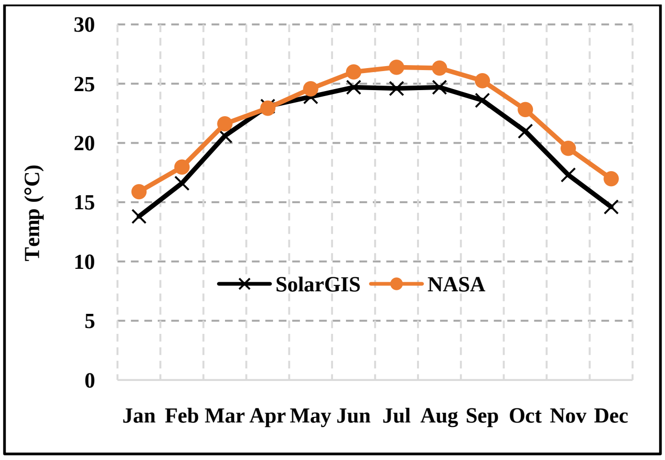

Fig. 7. Monthly long term average ambient air temperature

4 RESULTS AND DISCUSSION

4.1 Slope of PV Panels

Slope is the angle of inclination of the PV panels with horizontal axis of earth surface. In general slope of the panels is assumed equal to absolute value of latitude to maximize the annualenergy generation irrespective of the season of the year. The latitude of project location is 26.85° and hence the slope of PV panel should have been 26.85° to maximize the output throughout the year. In order to find optimum slope, the system was simulated for different inclination angle. From the simulation, the maximum energy generated was found to be at an angle of 23.5° as shown in Figure 8. However the solar panels were flush mounted on the building roof that has a pitch of 13°. Therefore in this paper, slope of the PV panel was taken as 13°.

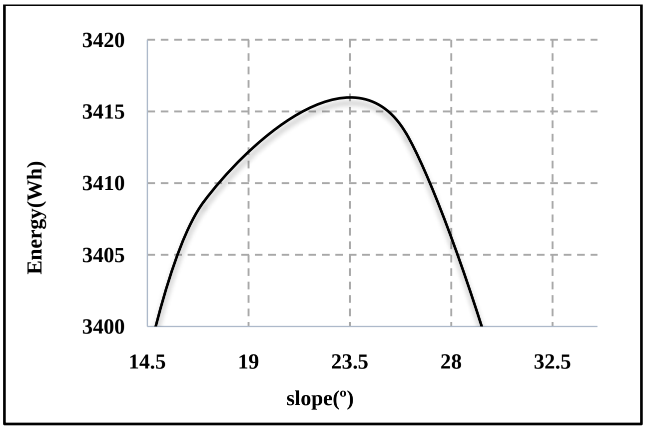

Fig. 8. Energy generated at different inclination of solar panels

4.2 Energy Generated

Both the systems were simulated for one year using climate data from SolarGIS. The climate data used was an average of 10 years data from 2004 to 2013. From the simulation it was found that total annual energy yield from grid-connected system is 8908 kWh and that from standalone system is 14093 kWh.The energy generated based on the HOMER model is 8718 kWh for grid-connected and 11152 kWh for standalone system. Compared to the HOMER model, TRSNSYS simulation gives higher output for the same system capacity and input data. The input data in case of HOMER model is monthly average whereas it is hourly data for TRNSYS.

The systems were re-simulated using the year 2013 climate data from Solar GIS. This was done to investigate the effect of using one year climate data against 10 years average data on the output of the simulation. When multiple year climate data is available, the conventional process is to take average of multiple year climate data to predict the performance of a system in future. Table 1 shows comparison of energy yield using 10 years average climate data and year 2013 climate data. From simulation, it was observed that the difference between energy yield from two different inputs is negligible (<0.5%). This indicates that whether one year data or average of 10 years data is being used as input for TRNSYS simulation, the annual yield is comparable. Therefore for the analysis purpose either data could be used for simulation.

TABLE 1: ANNUAL ENERGY YIELD

Input climate data used	**Grid-connected (kWh)**	**Standalone (kWh)**
Year 2013	7983	14050
10 Years average	8 908	14093
Difference	25	43
Output from Homer model	8 717	11 52

4.3 System Cost

The detail cost of the installed systems were presented by Seldon et al. (2015) which is reproduced in Table 2 and 3. The total cost of the system includes capital cost, operation& maintenance cost and replacement cost. The total life span of the project was assumed as 25 years based on the life span of the PV panels. During the project life time, battery bank has to be replaced 4 times as the life span of the battery is 5 years. The inverter need to be replaced two times as life span of inverter is 15 years. Including all the investment cost, operation& maintenance cost and cost of replacement, the total cost is $ 17898 and $ 36869 for grid-connected and standalone systems.

TABLE 2: GRD-CONNECTED CAPITAL COST

Parts	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)
PV	10773	0	750	0	11523
Converter	2480	4960	175	1240	6375
System	13253	4960	925	1240	17898

TABLE 3: STANDALONE CAPITAL COST

Parts	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)
PV module	13711	0	950	0	14661
Battery	6419	12838	158	5884	13531
Converter	3471	6942	0	1736	8677
Total	23601	19780	1108	7620	36869

4.4 Cost of Energy

The cost of energy (COE) was calculated based on the total cost of the system and total energy generated over the project life time.

$$COE = \frac{Total\ system\ cost}{Annual\ energy\ generated\ x\ Project\ life}$$

The COE for grid-connected system based on TRNSYS simulation is US$ 0.08/kWh which is same as estimate from HOMER model. However there is significant difference between the TRNSYS and HOMER model for standalone system, US$ 0.10/kWh based on TRNSYS simulation and US$ 0.13/kWh based on HOMER model (Table 4). The difference could be attributed to the difference in total annual energy generated which is higher in case of TRNSYS simulation.

TABLE 4: COST OF ENERGY

Model	Grid-connected (US$/kWh)	Standalone (US$/kWh)
TRNSYS simulation	0.08	0.10
HOMER Model	0.08	0.13

5 CONCLUSIONS

A 5.5kW grid-connected and 7 kW standalone solar PV systems were modelled in TRNSYS 17. The system was simulated for one year using input climate data from SolarGIS. The simulation results show that grid-connected system can generate 8908 kWh/year and that of standalone system can generate 14093 kWh/year. The corresponding estimated COE is $ 0.08/kWh and $0.1/kWh for grid-connected and standalone system respectively. Whereas from HOMER model, the COE for grid-connected system is $0.08/kWh and that of standalone system is $0.13/kWh.In TRNSYS simulation, whether one year data or average of multiple year data is used as input, the output is comparable and hence either of the data could be used as input data.

ACKNOWLEDGMENT

SonamWangchuk, LungtenNorbu and Chimi Rinzin would like to thank the College of Science and Technology for sponsoring this study. Tshewang Lhendup would like to thank the Global Environment Facility (GEF) and Small Grant Program through the United Nations Development Program (UNDP), Bhutan for funding 12.5 kW solar PV power plant at the College of Science and Technology, Phuentsholing.

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