OPTIMAL DESIGN OF A GRID CONNECTED SOLAR PHOTOVOLTAIC POWER SYSTEM FOR A RESIDENTIAL LOAD

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Abstract: The present paper uses the software Hybrid Optimization Model for Electric Renewables (HOMER) to design and analyze a non-autonomous power system which includes a grid connected solar photovoltaic (PV) based power system with battery storage to supply a residential load located near Siliguri, West- Bengal (with latitude and longitude of 26 072'N and 88 041'E respectively). For optimal system design the analyses have been carried out in two modes – grid connected as well as stand-alone. The simulation results of these two modes have been studied on the basis of cost of energy, pay-back period, environmental emissions etc. and compared with the grid-only (base) mode. Performance of each component (i.e. battery, inverter, rectifier etc.) of the model is evaluated and finally sensitivity analysis is performed to optimize the system out of different conditions.

Index Terms—HOMER, Solar PV, Levelized cost, Optimization

I. INTRODUCTION

With rapid escalation of prices, depletion of stocks, severe carbon emission and climate change impact of fossil fuel, on one hand, and on the other hand, sharp increase of capital cost, as well as high risk of blackouts of central generating plants, and at the end, deregulation of electricity markets, there is a focused attention on alternate generating system with higher efficiency of energy use. In the new millennium many countries have taken serious initiatives to tap renewable energy resources like solar, wind etc, which are abundant and environment friendly. These countries are funding hugely both in the research work and in the public awareness campaign for the protection of environment. High quality of research will bring down the cost of manufacturing as well as enhance the efficacy of the allied equipment (like solar PV for solar resources) for tapping these resources. And additionally public awareness will increase the market demand of these equipments. Thus the equipment will be sold out at the economy of scale. [1]-[2].

Solar photovoltaic is now, after hydro and wind power, the third most important renewable energy source in terms of globally installed capacity. More than 100 countries use solar PV. Driven by advances in technology and increases in manufacturing scale and sophistication, the cost of photovoltaic has declined steadily since the first solar cells were manufactured, and the levelized cost of electricity (LCOE) from PV is competitive with conventional electricity sources in an expanding list of geographic regions. Net metering and financial incentives, such as preferential feed-in tariffs for solar-generated electricity, have supported solar PV installations in many countries. Solar PV systems convert solar energy into electricity which can then be used by a household. If a household needs more electricity than the solar PV system can provide, this additional electricity can be drawn from the electricity grid. If the solar PV system is producing more electricity than the household needs, the excess electricity can be sold back to the grid. PV system should supply the electric power to the interrupted customers considering the discharge rate of batteries. Without storage, solar PV, typically, contributes less than 40% of its rating towards distribution capacity. [3] - [7].

Extensive research was made in the field of grid connected PV system. Indradip Mitra and S.P.Gon Chaudhuri [8] have given a plan for Remote Village Electrification through Renewable Energy in the Islands of Indian Sundarbans. A technical report was prepared by T. Givler and P. Lilienthal using HOMER Software, NREL's Micropower Optimization Model, to Explore the Role of Gen-sets in Small Solar Power Systems in Sri Lanka [9]. Anagreh et al [10], investigated the potential of solar energy for seven sites in Jordan and created a motivation of use of solar PV based power system. Yousif El-Tous [11] also performed a case study on the effect of the incentive tariff on the economic feasibility of a grid-connected of a Grid-connected PV Household System in Amman. Li et al [12], presented a study of a grid-connected PV system in Hong Kong, and showed that the payback period was estimated as 8.9 years. Gerry and Sonia [13], studied to maximize energy output from distributed energy resources (DERs) by Optimization using HOMER. They also evaluated Performance of each component of the model and finally they performed sensitivity analysis to optimize the system at different conditions. Sopian et al [14] performed the optimization of a stand-alone PV hybrid system using HOMER simulation software for a household in Malaysia.

This paper presents an analysis for a grid-connected photovoltaic system for a residential house in Siliguri (west Bengal). System optimizations are studied both at grid connected and stand-alone cases. Comparison between these cases as well as with grid-only (base) case are done on the basis of cost of energy, pay-back period, environmental emission etc. Sensitivity analysis finally tells the best optimal result out of different options. The system is simulated and optimized using HOMER.

II. SYSTEM MODEL

Research method –

The proposed model consists of solar photovoltaic modules of 2 kW PV system, a grid connected converter of 2 kW capacity with an H-1000 battery storage. The system is designed to have a life time of 25 years so the PV panels will not be replaced. The proposed system is shown in Fig.1.

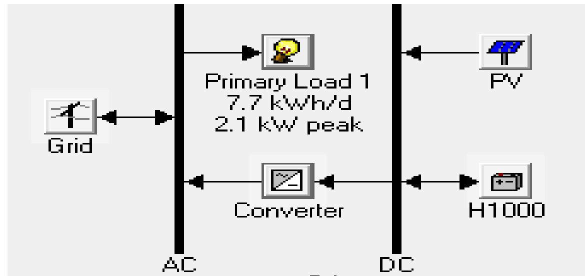

Fig. 1: System Configuration using HOMER

A. Daily Load Profile

A typical house in Siliguri is chosen for case study. The daily electrical load profile in the proposed area is based on basic demands of utilities such as lighting, fan, refrigerator, television and other household appliances etc (Table I).

The average daily load profile data is shown in Fig. 2. Also the seasonal profile for the load is given in Fig. 3. Both these figures are prepared by the HOMER software based on the input data of the daily load profile.

TABLE I

Total average energy consumption

Appliances	Quantity	Power	Hours Used per Day(h/day)	Energy (Wh/day)
Celling Fan	2	120	12	1440
Refrigerator	1	80	16	1280
Television	1	130	4	520
Fluorescent Lamp	2	80	7	560
CFL	4	88	6	528
Washing Machine	1	500	1	500
Water Pump	1	500	1	500
Computer Desktop	1	300	5	1500
Geyser	1	2000	0.25	500
Electric Iron	1	1000	0.2	200
Night Lamp	2	10	6	120
Total Energy Consumed per Day			=	7648 Wh

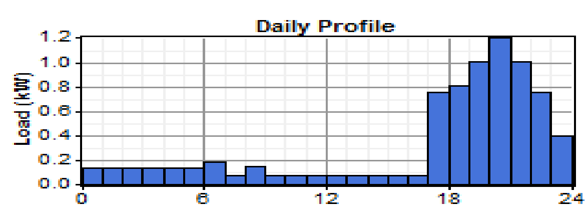

Fig. 2: Average load profile.

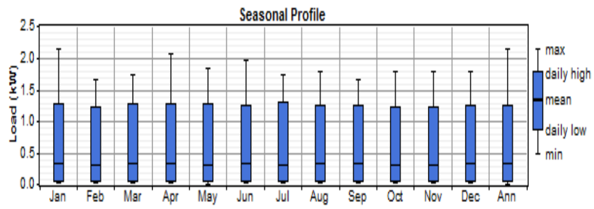

Fig. 3: Seasonal load profile.

B. Solar PV modules

Solar resource indicates the amount of global solar radiation that strikes earth's surface. Solar radiation for this study area was obtained from the NASA Surface Meteorology and Solar Energy website [15], [16], [17]. An average solar radiation of 4.788 kWh/m2/day and a clearness index of 0.533 is obtained for the study area (Table II). The clearness index is a measure of the clearness of the atmosphere and which is expressed by the fraction of the solar radiation that is transmitted through the atmosphere to strike the surface of the Earth. The Solar irradiation and Global horizontal radiations at Siliguri are shown in Table II & Fig.4 respectively.

The PV array modeled in HOMER gives DC output in direct proportion to incident solar radiation. The installation cost of PV array is taken $2000/kW [18] and replacement cost is $1800/kW. Operation and maintenance (O&M) cost is practically zero and its lifetime is 25 years. For consideration of the degrading factors caused by temperature, soiling, tilt, wiring losses, shading, snow cover, aging etc. a derating factor of 80% is applied to each panel.

TABLE II

Solar Radiation and Clearness Index Data for Siliguri [15]

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.629	4.030
February	0.654	4.950
March	0.643	5.820
April	0.594	6.140
May	0.539	5.970
June	0.438	4.950
July	0.375	4.190
August	0.401	4.240
September	0.418	3.960
October	0.596	4.760
November	0.672	4.470
December	0.664	4.000
Average:	0.533	4.788

Fig. 4: Global Horizontal Radiation

C. Converter

Here the converter is used only in inverter mode. The unidirectional converter capital costs and replacement cost are assumed to be$850/kW and $25 respectively for a lifetime of 30 years. The operating and maintenance cost assumed is nil [11]. The inverter efficiency is assumed to be 90%.

D. Grid

The cost of electrical energy is taken to be $ 0.08/kWh for purchase and $ 0.21 /kWh for sale back to the grid [19].

E. Battery

As the system considered working 24 hours, battery is also taken as a main part of the system. Here Hoppecke 10 OPzS 1000 is chosen because it is capable of giving required back up during load-shedding. The capital cost and replacement cost are both taken as $439 [20].

III. EXPERIMENT AND RESULT

Optimization Result

From the optimization results the best optimal system is designed in which components are 2 kW PV-Array and 2 kW converter and 1battery. The analysis also reveals that in case of load shedding or even grid failure the selected no of battery bank can give the necessary back up for 5 hours to run one ceiling fan and one fluorescent lamp.

Simulation Result& Discussion:

Simulation is performed with specified data using HOMER to obtain the optimal result for the system of Fig. 2. The simulation results for various cases are as given below.

Case1: Grid only System (Base Case):

Here Yearly Electricity Production & Consumption data are given in Table III. In this case total net present cost (NPC) is obtained as $2882 and levelized cost of energy (COE) is obtained as $0.080/kWh. Yearly emissions of Base case are given in Table IV.

TABLE III

Yearly Electricity Production & Consumption in Grid Only System

Production	kWh/yr	%	Consumption	kWh/yr	%
Grid purchases	2,818	100	AC primary load	2,818	100
Total	2,818	100	Total	2,818	100

TABLE IV

Yearly Emissions of Grid only System (Base Case)

Pollutant	Emissions (kg/yr)
Carbon dioxide	1,781
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	7.72
Nitrogen oxides	3.78

CaseII: Grid Connected PV System:

In this case converters are operated in inverter mode. PV module, alone, will charge the battery.

From Table V we can see that Yearly Electricity Production & Consumption are 5569 kWh and 5191 kWh respectively. Also the amount of yearly converter losses (i.e. 307 kWh) is given in Table VI. From simulation result we can also see that 70kWh/year and 1kWh/year energy are lost due to battery loss and battery storage depletion respectively. So amount of yearly electricity production, consumption and total losses (i.e. 6.78% of total electricity production and 13.4% of total electricity consumption by primary load) show that the system is highly efficient. Also from Table VII it reveals that the amount of excess electricity, though negligible, is 0.267 kWh / year. It has been checked that total electricity production and consumption including all losses are balancing properly.

TABLE V

Yearly Electricity Production & Consumption

Production	kWh/yr	%
PV array	3,138	56
Grid purchases	2,431	44
Total	5,569	100

Consumption	kWh/yr	%
AC primary load	2,818	54
Grid sales	2,373	46
Total	5,191	100

TABLE VI

Yearly Electrical Power Losses in Converter

Quantity	Inverter	Rectifier	Units
Hours of operation	4,421	0	hrs/yr
Energy in	3,067	0	kWh/yr
Energy out	2,760	0	kWh/yr
Losses	307	0	kWh/yr

It is shown in Table VII that total net present cost (NPC) is obtained as $2805 and levelized cost of energy (COE) is obtained as $0.078/kWh. From the results it is clear that cost of energy is lower as compared to grid alone system. So this system is feasible from economic point of view. Also payback period for present system is obtained as 12.4 years (Table VIII) which ensures approximate 13 years of net income for a project life of 25 years.

TABLE VII

Different Cost & Renewable Fraction of Present System

Total NPC: $ 2,805
Levelized COE: $ 0.078/kWh
Operating Cost: $ -261/yr

Quantity	kWh/yr	%
Excess electricity	0.267	0.00
Unmet electric load	0.00	0.00
Capacity shortage	0.00	0.00

Quantity	Value
Renewable fraction	0.563

TABLE VIII

Economic results

	PV (kW)	H1000	Conv. (kW)	Grid (kW)	Initial Capital	Total NPC
Base case				1,000	$ 0	$ 2,882
Current system	2	1	2	1,000	$ 6,139	$ 2,805

Metric	Value
Present worth	$ 76
Annual worth	$ 6/yr
Return on investment	7.92 %
Internal rate of return	6.13 %
Simple payback	12.4 yrs
Discounted payback	24.6 yrs

The amount of yearly emissions of the present system is given in Table IX. In this case amount of emission of CO2, SO2 and nitrogen oxides reduced to 36.3kg/year, 0.158 kg/year, 0.077 kg/year respectively. These values are very much lower than the grid-only system. Hence this system is beneficial in the context of clear environment, too.

TABLE IX

Yearly Emissions of Present System

Pollutant	Emissions (kg/yr)
Carbon dioxide	36.3
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	0.158
Nitrogen oxides	0.077

CaseIII: PV System not Connected with Grid (stand-alone system)

In this case, firstly we have simulated the stand alone system with various combinations of loads. Finally we have achieved the optimal condition in which the system is capable of giving back up during load shedding or during grid failure for 5 hours with one fan and one fluorescent lamp during night.

The detailed simulation results of this condition regarding Yearly Electricity Production & Consumption, amount of yearly converter losses and different cost data are shown in Table X, Table XI & Table XII respectively. Here simulation results also show that total energy loss occurred in battery is 33 kWh/ year.

TABLE X

Yearly Electricity Production & Consumption in Stand – alone System

Production	kWh/yr	%
PV array	3,138	100
Total	3,138	100

Consumption	kWh/yr	%
AC primary load	562	100
Total	562	100

TABLE XI

Yearly Electrical Power Losses in Converter Stand – alone System

Quantity	Inverter	Rectifier	Units
Hours of operation	5,839	0	hrs/yr
Energy in	624	0	kWh/yr
Energy out	562	0	kWh/yr
Losses	62	0	kWh/yr

In this case the amount of excess electricity is 2481 kWh /year (Table XII). There are a few occasions when the grid fails. So, this excess electricity will reduce proportionately. Table XII also shows that amount of NPC and COE becomes $6279 and $ 0.874 / kWh which are very high. But as we know grid failure or load shedding are not common phenomena in a good power system so we can say the system is feasible during emergency condition.

It is also important to note that the yearly emission during standalone condition, as shown in Table XIII, is nil.

TABLE XII

Different Cost & Renewable Fraction of Stand – alone System

Total NPC: $ 6,279
Levelized COE: $ 0.874/kWh
Operating Cost: $ 11/yr

Quantity	kWh/yr	%
Excess electricity	2,481	79.1
Unmet electric load	0.334	0.1
Capacity shortage	0.535	0.1

Quantity	Value
Renewable fraction	1.00

TABLE XIII

Yearly Emissions of Standalone System

Pollutant	Emissions (kg/yr)
Carbon dioxide	0
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	0
Nitrogen oxides	0

IV. CONCLUSION

Amount of yearly energy production, consumption and finally COE have been obtained at different conditions to get the optimum system. The analysis reveals that the COE is $0.078/kwh in case of the grid connected system (Case II) - lower as compared to grid only system. This is advantageous in context of economy. But in case of standalone system the COE becomes $0.874/kwh (case III). So in case of standalone system the COE is higher as compared to grid only system. But we will not bother as standalone system is useful only in case of emergency condition (during load-shedding).

Another important advantage of this approach is that in case of load-shedding & grid power failure battery can give the required back up for emergency load. Here 1 no of battery is selected for back up. Because if we take more no of batteries, the system will be very costly as both NPC and COE will increase. However the system with one battery is capable of giving back up for 5 hours with one fluorescent lamp and one ceiling fan.

It is noteworthy that Solar-based-powered systems are more beneficial to the environment as compared to grid only system whether they are located in highly populated or remote areas. Due to incorporation of solar PV to the grid, it reduces the carbon di-oxide and other harmful gases emission to a large extent in environment.

Though capital investment is very high still the estimated payback is obtained at 12.4 years so for a long run system it is highly profitable. Also it has a low operating and maintenance cost. It also enables to improve the economic development and living standards of remote area. This situation will also improve as the capital cost of PV systems decrease with maturing of technology.

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