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The Techno-Economic and Environmental Assessments of Grid-Connected Photovoltaic Systems in Bhubaneswar, India

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Abstract**—**The power system utility has started to think about the green power technology in order to have an eco-friendly environment. The green power technology utilizes renewable energy sources for reduction of GHG emissions. Odisha state (India) is very rich in potential of renewable energy sources especially in solar energy (about 300 solar days), for installation of grid connected photovoltaic system. This paper focuses on the utilization of photovoltaic systems in an Institute building of Bhubaneswar city, Odisha. Different data like solar insolation (kW/m^2/day), sunshine duration has been collected from metrological stations for Bhubaneswar city. The required electrical power and cost are calculated for daily load of 1.0 kW. The HOMER (Hybrid Optimization Model of Electric Renewable) software is used to estimate system size and its performance analysis. The simulation result shows that the cost of energy (COE) is $ 0.194/kWh, the Operating cost is $63/yr and the net present cost (NPC) is $3,917. The energy produced from PV array is 1,756kWh/yr and energy purchased from grid is 410kWh/yr. The AC primary load consumption is 1314 kWh/yr and the Grid sales are 746 kWh/yr. One battery is connected in parallel with 12V DC Bus and the usable nominal capacity 2.4 kWh with 9.6 h autonomy capacity.

Keywords**—**Economic assessment**,** HOMER**,** Optimization, Photovoltaic (PV), Renewable energy.

I. INTRODUCTION

ENERGY is considered as main reagent in the generation of wealth and a significant factor in the economic development of every nation. The global demand for energy is rapidly increasing with increasing population, urbanization, modernization and is expected to rise sharply over the forthcoming years. Energy consumption grows at a rate of approximately 1% and 5% per year in developed and developing countries respectively [1]. The future demand for electricity is assessed from time to time by the International Energy Agency (IEA), which shows that the world's electricity consumption is projected almost to double by the year 2020 [2]. Fossil fuels, which have been primary source of energy generation, are facing rapid deterioration, and appear to be insufficient to match the near future energy demands of the world. Moreover, fossil fuels inflict enormous impacts on the environment. Climatic changes driven by energy production are in particular the production of greenhouse gas (GHG) emissions, directly impact the environment. According to the world health organization (WHO), as many as 1,60,000 people die each year from the side-effects of climate change and the numbers could almost double by 2020 [3]. Therefore, meeting the rapidly increasing global energy needs, without irreparable environmental damage require long-term potential actions for sustainable development. In this regard, renewable energy resources appear to be one of the most efficient and effective solutions [4].

Solar energy is one of the most promising renewable energies. The amount of annual solar energy reaching the Earth's surface is about 10,000 times more than annual global energy demand, but only 0.01% of the solar energy reaching the Earth is to be harnessed to fulfill the world energy requirements. The solar energy is utilized in two ways; solar thermal to supply heat using solar collectors and solar photovoltaic to generate electricity using PV cells [5], [6]. Photovoltaic generators which directly convert solar radiation into electricity have a lot of significant advantages such as being inexhaustible and pollution free, silent, with no rotating parts, and with size-independent electric conversion efficiency. However, between 1976 and 2013, the capital cost of PV modules per watt of power capacity has decreased from more than $58 per watt to less than $2 per watts [7], [8].

Generally two types of the photovoltaic systems, stand-alone PV system and grid-connected system are used.

The solar energy generated is matched to the energy demand in a stand-alone system by using storage system (batteries). In grid-connected systems, the public electricity grid functions as an energy store. In some cases, storage devices are used to improve the availability of the power generated by the PV system [9]. In the following sub-sections, more details about different components of the PV system are presented and the recent related research activities are discussed. The system consists of PV modules, DC-DC converter, DC-AC inverter, filters, modules structure, wiring, fuses, and other system safety devices. The building blocks of a grid-connected photovoltaic system are shown in Fig. 1. The matrix of PV arrays converts the sunlight to DC power, raised by DC-DC converter .The inverter unit converts the DC power to AC power. The generated AC power is injected into the grid and/or utilized by the local loads.

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The effect of various parameters in the design of grid connected PV system is done by different authors [10]. The main factors that affect system's design are the initial capital cost, the selling price of the generated energy and the grid connected PV system capital cost subsidization. The TRNSYS simulation tool is used for the exploration of the impact of PV surface inclination on the grid connected PV system energy production [11]. The detailed size and design optimization of grid connected PV system is carried out using genetic algorithm to determine the optimal number of modules, the configuration of the arrays, the PV module tilt angles, number of inverters, allocation of PV modules among the converters and dimension of the actual installation area[12]-[14].

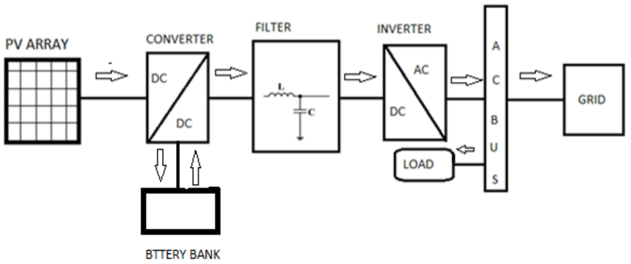


Fig. 1 Block diagram of Grid-connected PV system

II. HOMER SIMULATION MODEL

Fig. 2 represents the system economic analysis, which is done by using the HOMER software developed by the National Renewable Energy Laboratory (NREL) [15]. It is a computer model that evaluates the design options for both off-grid and grid-connected energy systems applications. The optimization and sensitivity analysis gives the economic and technical feasibility of different options. It also assists in understanding and quantifying the effects of uncertainty or changes in the inputs.

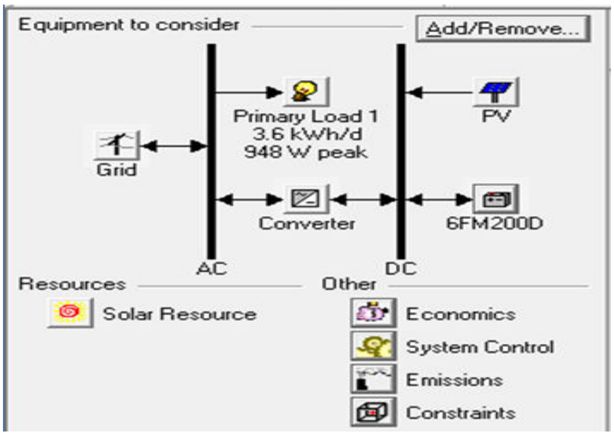


Fig. 2 All components of Grid connected PV system by HOMER

In this paper, the work has been carried out for a grid connected PV system to save energy. The HOMER software is used for designing and analyzing hybrid power system, whose performance based on energy supplying with regard to the lowest cost. With considering economic parameters such as inflation rate, Net present cost (NPC), and the cost of energy (COE) is calculated.

III. SITE CHARACTERISTICS

Bhubaneswar is the capital and largest city of state Odisha, India with political, cultural and commercial centre and located on latitude 20.183 N and longitude 85.617E having populated by 41million (2010 data). It has a tropical savannah climate. The annual mean temperature is 27.4°C. Summers (March to June) are hot and humid, with temperature as low as 30^{0}C and during dry spells; maximum temperatures often exceed 40°C. Winter lasts for only about ten weeks, with seasonal lows dipping to 15–18°C in December and January. Rains brought by the Bay of Bengal branch of the south west summer monsoon lash Bhubaneswar between June and September, supplying it with most of its annual rainfall of 1,542mm (61 in). The location of Odisha is shown in Fig. 3 and the location of Bhubaneswar is shown in Fig. 4. The investigated location has appropriate irradiance (3-6 kWh/m^2/d).

Fig. 3 Site Location of Odisha in India map

Fig. 4 Site Location map of Bhubaneswar

A. Solar Energy Resources

Solar insolation and clearness index for Bhubaneswar is collected from HOMER software and graphs are shown in Fig. 5. The average solar radiation is found to be 4.81kWh/m^2/day with average clearness index 0.511.

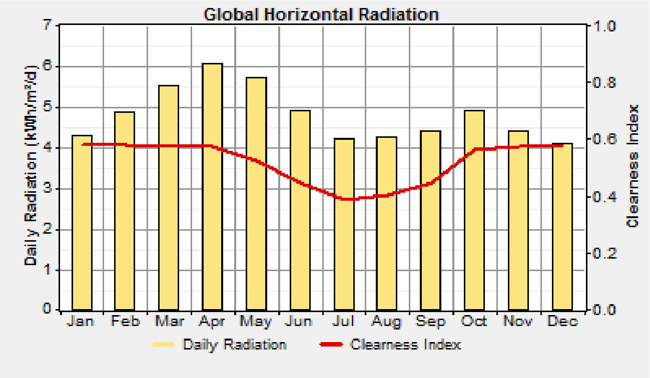


Fig. 5 Monthly average solar radiation with clearness index in a year

B. Load Pattern

The hourly load consumption of the Institute building is shown in Fig. 6. This shows that load is highest from 11AM to 1 PM and also at 4 PM. and the load profile throughout the year is shown in Fig. 7.

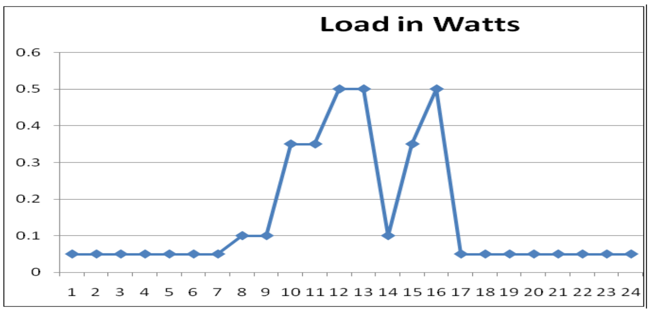


Fig. 6 Hourly load profile

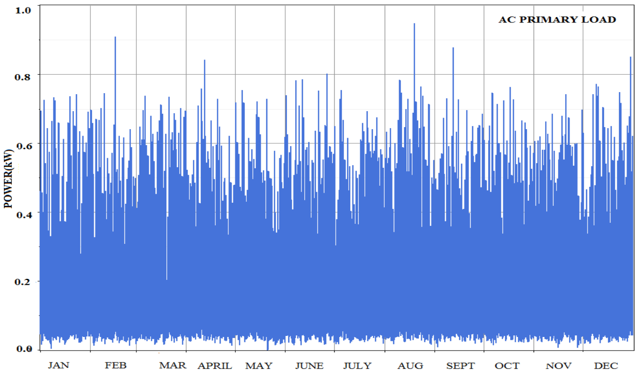


Fig. 7 The load profile throughout the year

IV. Energy System Components

A. Photovoltaic Array

The suggested PV panels of 250W each is used in the system of 1kW. The panels are modeled as fixed and tilted south at an angle equal to the latitude of the site over the Institute building, which is shown in Fig. 8.

The existing PV array is comprised of 4 Waaree Solar PV crystalline silicon modules, as seen in Fig. 8. Each module is consists of 72 cells in 6 columns and 12 rows. The PV power throughout the year is calculated by HOMER software and the yearly graph is shown in Fig. 9.

Table I shows the technical specifications of each PV module from datasheet.

Fig. 8 Rooftop PV system

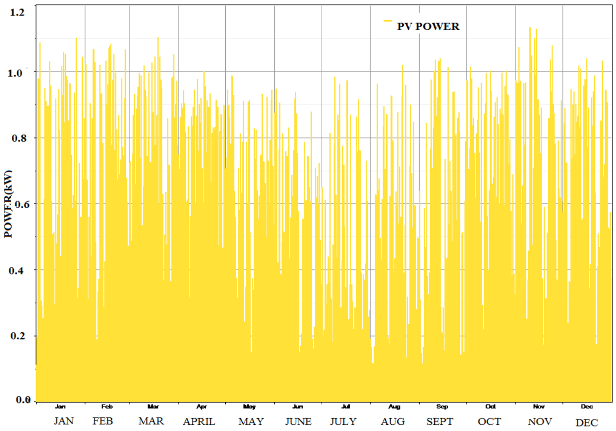


Fig. 9 PV power available throughout the year by HOMER

TABLE I
Technical Specifications of Each PV Modules

Technical specifications	Unit
Nominal voltage	24V
Maximum power(Pmax)	250 W
Open Circuit Voltage (Voc)	48 V
Short Circuit Current (Isc)	7.75 A
Voltage at maximum power(Vmp)	35 V
Current at Maximum Power (Imp)	7.14A
Maximum System Voltage	1000V
Temp. Coefficient of Isc	+4.4mA/^{0}K
Temp. Coefficient of Voc	-0.123V/^{0}K
Temp. Coefficient of power	-0.47%/^{0}K
NOCT(Air20C,Sun1kW/m2,wind0.5m/s)	47(+/-)2^{0}C
Number of solar cells	72
Matrix connected in series	6X12

The estimated capital and replacement cost of panel is US$ 2/W. This cost includes shipping, tariffs, mounting hardware, control system, wiring, installation, and dealer mark-ups. The lifetime is assumed to be 25 years having derating factor of 80% applied to the electric production from each panel.

B. Characteristics of the PV Module Using MATLAB

The waveforms obtained by varying the solar insolation and temperatures which are fed into the PV array model have been plotted as shown below. Fig. 10 shows the current (I) and voltage (V) characteristics with variable solar irradiance (200-1000w/m2) at constant temperature 27^{0}C.

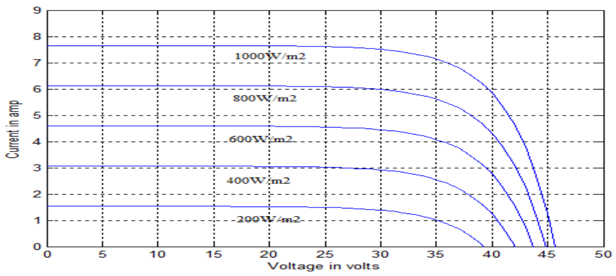


Fig. 10 I-V curves for constant temperature and variable irradiance

It is observed that with increasing the solar radiation at constant temperature the voltage and current output increases. Hence at higher insolation the required level voltage is obtained.

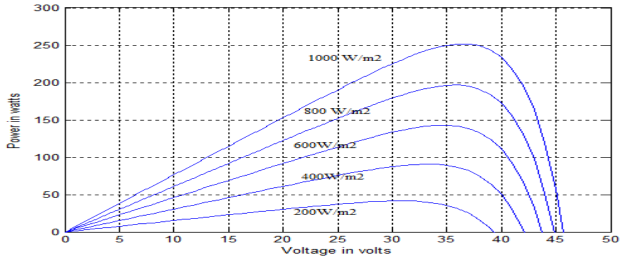


Fig. 11 P-V curves for constant temperature and variable irradiance

From Fig. 11, it is observed that by increasing the solar insolation level, the power output from PV array increases.

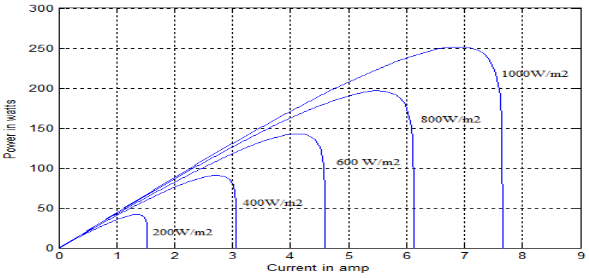


Fig. 12 P-I curves for constant temperature and variable irradiance

From Fig. 12, it is observed that with increasing the solar radiation level, the current and power output increases.

The higher the temperature, lower the output voltage, current and power which is shown in Figs. 13-15.

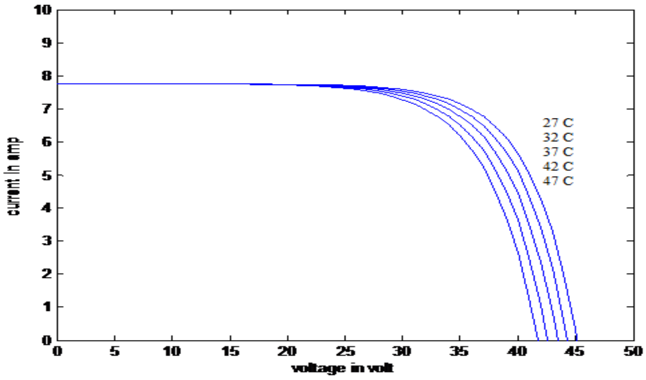


Fig. 13 I-V curves for variable temperature and constant irradiance

From Fig. 13, it is observed that the increasing the temperature level at constant irradiance, the voltage output from PV array decreases but current output increases slightly with respect to voltage and, hence the power output from PV array decreases. The power-current and power voltages are shown in Figs. 14 and 15.

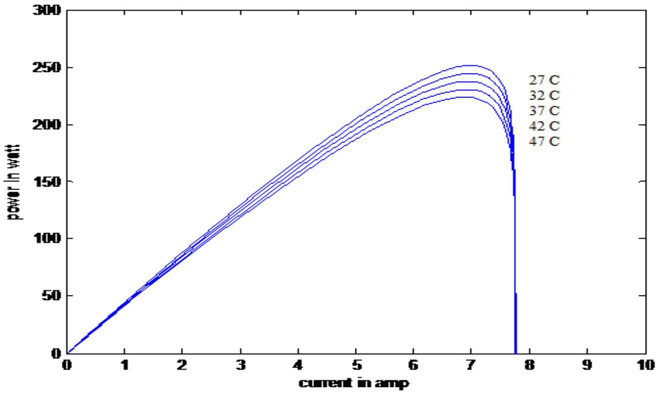


Fig. 14 P-I curves for variable temperature and constant irradiance

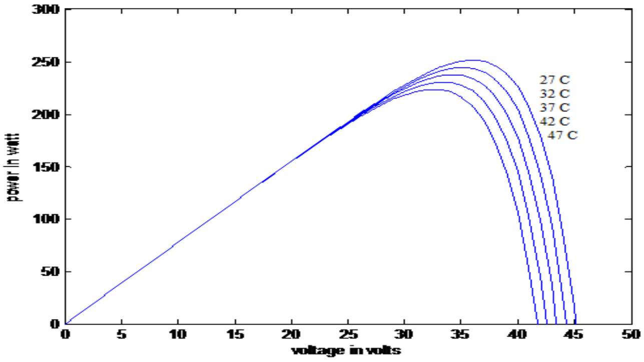


Fig. 15 P-V curves for variable temperature and constant irradiance

The efficiency (η) of solar module is calculated according to (1) given below.

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{max}*I_{max}}{G*A} \qquad (1)$$

where, P_{max} is maximum power, P_{in} input power, V_{max} maximum voltage, I_{max} maximum power, G, solar radiation (W/m^2), A is area of solar module in (m^2).

The average efficiency of the PV module is simulated by the MATLAB programming and the result is shown in Table II.

TABLE II
OUTPUT OF PV MODULE AT DIFFERENT SOLAR RADIATION FROM SIMULATION

G(W/m^2)	A(m^2)	V_{max}(V)	I_{max}(A)	V_{oc}(V)	I_{sc}(A)	η(%)
200	1.643	33.5	1.20	42.0	1.60	13
400	1.643	34.5	2.80	44.6	3.20	15
600	1.643	35.5	4.00	46.2	4.80	14
800	1.643	36.5	5.50	47.0	6.20	15
1000	1.643	37.5	7.14	48.0	7.75	15

C. Selection of Inverter

Inverters of 1.0 kW is considered in the analysis. The estimated price of an inverter is US$ 2/W, and its lifetime is taken as 20 years. During the 4,380hrs of operation in a year, the energy in to the inverter is 1,756kWh and energy out from the inverter is 1,650KWh. So, the losses occurred in inverter are 6%.

D. Battery Bank

Lead-acid batteries are most widely applied storage solutions in this system. The operational principle of an energy storage system is based on the accumulation of available energy surplus in order to be used during shutdown of Grid supply. In this system one battery is in parallel with 12V Bus voltage and the usable nominal capacity 2.4 kWh with 9.6 hr autonomy capacity is used with 100% state of charge is shown in Fig. 16.

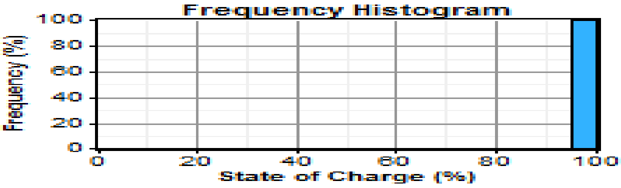


Fig. 16 State of charge of battery with frequency

1. Electrical Output of the System

The electrical output of the system including PV and Grid is shown in figure below. Out of total production, PV is having 81% renewable fraction and the Grid having 19% contribution, which is shown in Fig. 17.

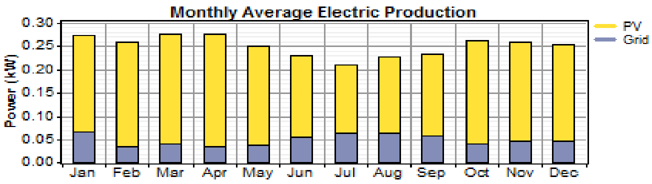


Fig. 17 Annual energy production by PV and Grid

2. Grid Activity

During the whole year, the detailed energy purchased, energy sold, is given in Fig. 18. The annual energy purchased is 423 kWh and energy sold is 753kWh. So, net energy sold to the Grid is 330kWh.

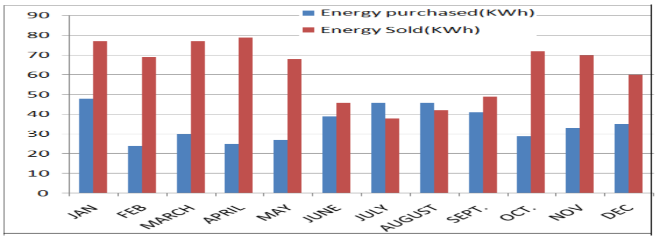


Fig. 18 Electrical energy to and from the Grid system during one year

V. ECONOMIC ANALYSIS OF THE PV SYSTEM

The economic benefit of using PV system is mainly of reducing Grid electricity consumption. A number of factors influence the costs of PV system such as the installed system and maintenance costs. The life cycle cost of the PV systems are estimated by considering the life cycle of the PV system components for 20 years except for the batteries, which is considered a life of 10 years.

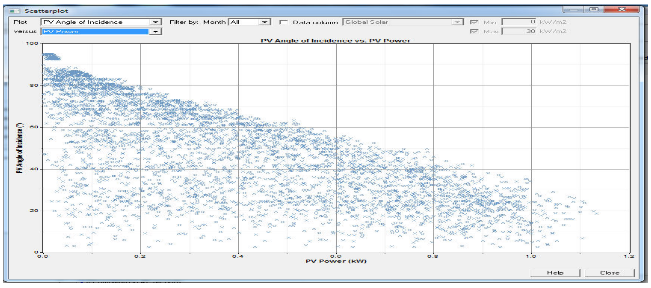
TABLE III
DETAILED ECONOMIC ANALYSIS OF PV SYSTEM BY HOMER SOFTWARE

PV (kW)	Initial Capital	Operating Cost($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Batt. Lf(yr)
	$1,000	151	$2,486	0.193	0.00	
	$1,500	181	$3,273	0.254	0.00	10.0
1.0	$3,000	44	$3,429	0.169	0.80	
1.0	$3,300	63	$3,917	0.194	0.80	10.0

Table III shows the optimization results of the system having initial capital cost $3,300, total net present cost(NPC) $3,917 and the cost of energy(COE) is 0.194$/kWh.

VI. SYSTEM ANALYSIS

Fig. 20 shows a typical daily operating pattern of a grid connected PV system. From the graph, it is concluded that the PV power is greater than load demand from 7AM to 5 PM. But the load between 5PM to 7AM is fulfilled by battery storage system. The Grid power sales are much higher than the Grid power purchase. From the Fig. 19, it is found that when the PV angle of incidence is higher, the output power from PV panel is lower and is maximum when PV angle of incidence is equal to latitude of that place.



Plot: PV Angle of Incidence
versus: PV Power
Filter by: Month All
☐ Data column: Global Solar
☑ Min 0 kW/m2
☑ Max 30 kW/m2

Fig. 19 PV angle of incidence versus PV power

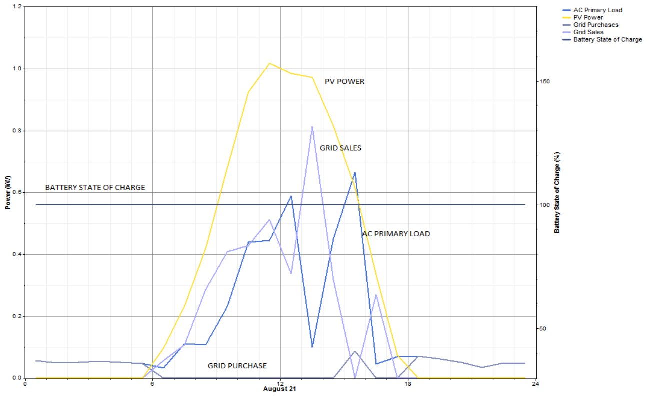


Fig. 20 A daily operating pattern of a grid connected PV system

VII. EMISSIONS

By adapting renewable-energy technologies (only solar energy), the emission of all these harmful gases can be substantially reduced, which is shown in Table IV.

TABLE IV
EMISSIONS DETAILS

Pollutant	Emissions (kg/yr)
Carbon dioxide	-208
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	-0.904
Nitrogen oxides	-0.442

VIII. CONCLUSION

Photovoltaic systems can provide a clean and reliable energy and environmentally friendly source of power. In addition, the cost of photovoltaic energy is decreasing gradually as the market demand and production of PV systems increases. This paper studies the feasibility of utilizing the photovoltaic systems in an Institute of Bhubaneswar, India. Using the HOMER software computer model for latitude 20.183 N and longitude 85.617E, it is found that the most economic system for Institute building having a daily load of 3.6 kWh is consists of 1-kW PV array(4 modules,250w each) one battery (12 V) and 200Ah capacity, 1-kW inverter and a 1000-kW Grid. The total initial capital cost, net present cost, and cost of electricity produced from the system are US$ 3,600, US$ 4,876, and US$ 0.185/kWh with 81% renewable fraction. But when the Grid supply with battery supported converter is used, the initial capital cost, net present cost, and cost of electricity produced are of US$ 3,300, US$ 3,917, and US$ 0.194/kWh, respectively. By adapting renewable-energy technologies, the emission of all these harmful gases can be substantially reduced.

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