

Techno-Economic Optimization and Sensitivity Assessment of Hybrid Renewable Energy Systems for Reliable Rural Healthcare Electrification

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ABSTRACT:

Rural healthcare centers predominantly depend on grid electricity supported by diesel generators, resulting in high operating costs, unreliable power supply, and increased environmental pollution due to the continuous operation of critical medical equipment. To address these challenges, this study presents the design, techno-economic optimization, and sensitivity assessment of hybrid renewable energy systems (HRES) for the Area Health Centre located in S. Kota, Vizianagaram, India. The annual hourly load profile of the healthcare facility is estimated based on electrical demand analysis, while solar radiation data are obtained from the NASA database and biomass resource availability is collected through field survey records. Various standalone and grid-connected hybrid configurations, including standalone PV, PV-grid, standalone biomass, biomass-grid, PV-biomass, and PV-biomass-grid systems, are modeled and optimized using HOMER Pro software. The systems are evaluated based on technical, economic, and operational performance indicators such as Net Present Cost (NPC), Levelized Cost of Energy (LCOE), renewable fraction, and payback period. The results indicate that the PV-grid hybrid system is the most economically feasible configuration, comprising 85 kW of photovoltaic capacity and a 67.2 kW converter, with an LCOE of \$0.0148/kWh, NPC of \$29,266, renewable fraction of 72.3%, and payback period of 1.40 years. Furthermore, a comprehensive sensitivity analysis is conducted by varying electrical load, solar radiation, nominal discount rate, derating factor, ambient temperature, PV efficiency, inflation rate, grid sellback price, and net-metering conditions to evaluate system robustness under uncertain operating and economic scenarios. The findings demonstrate that grid-assisted renewable energy systems can significantly enhance the reliability, economic viability, and sustainability of rural healthcare electrification.

Keywords: Hybrid energy system, Simulation, Optimization, sensitivity analysis, Payback period, Net present cost, Cost of Energy, Standalone PV, PV-grid, Standalone biomass, Biomass-grid, PV-biomass, PV-biomass-grid.

1. INTRODUCTION

The Indian healthcare sector emits 39 million tons of CO₂ annually, equivalent to the emissions from 10 coal-fired power plants [1]. Most healthcare centres are heavily reliant on thermal power plants. As a result, emissions from using thermal power plants are increasing continuously. To reduce emissions, renewable energy sources are considered due to their abundant availability. However, solar PV and biomass are intermittent sources, as solar energy is unavailable at night and biomass availability is not continuous. To address this issue, a combination of two or more energy sources should be used to ensure an uninterrupted power supply and to ensure long-term availability.[2] Typically, a hybrid energy system consists of renewable energy sources, energy

storage, a diesel generator or Grid backup, loads, converters, etc.[3]. The hybrid energy system can be classified into stand-alone, off-grid and on-grid systems. On-grid systems are connected to the local grid, which allows us to meet energy demand by integrating the renewable energy sources and the grid. The excess power is sold to the grid, and the shortage of power is purchased from the grid. In off-grid systems, energy demand is supplied by a renewable energy system which is not connected to the grid. The storage technologies, like batteries, are used for the storage of electricity when there is excess and used when there is a shortage [4]. Few studies have been carried out on the techno-economic aspects of various hybrid energy systems in different sectors, which are discussed here. Mendu et al. [5] analyse the different integrated hybrid energy systems for an educational institute and show that on-grid integrated energy systems are more optimal than stand-alone integrated energy systems. Dekkiche et al. [6] study describes the techno economic study of grid connected PV/Reformer/Fuel cell hybrid system with distinct solar tracking devices to supply electricity for a small city of Algeria and concluded that Vertical Single Axis Tracking is the most cost effective with the lowest cost of energy of 0.0360 \$/kWh.

Singh et al. [7] analysed the techno economic assessment of solar PV, fuel cell, and biomass gasifier hybrid energy system for energy centre MANIT Bhopal and reveals that this generate excess electricity of 36 kWh/year with zero percentage unmet electric load and the COE of biomass gasifier generator set, solar PV & fuel cell hybrid energy system is found be 15.064 ₹/kWh. Ali et al. [8] presented the optimum design of a hybrid renewable energy system for sustainable energy supply to a remote island and a comparison of two hybrid energy systems based on NPC and COE of the system. Udofia et al. [9] Study describes the technical feasibility and economic viability of an optimal hybrid renewable energy system for rural electrification and concluded that the PV/Diesel generator-battery bank configuration is the optimal system with a COE of \$ 0.062/kWh. Bhandari et al. [10] presented physical modelling of PV-Wind hybrid energy systems and a comprehensive review on various optimisation techniques and showed that instead of a single generation system like PV or Wind, HRES can harvest energy even when the potential of one is minimal, which increases power reliability. Tilahun et al. [11] Study analyses a holistic design optimisation scheme of a hybrid plant for industry energy supply. Design and analysis showed that a hybrid plant efficiency of 31.5% with 23.5% solar gain. Rosen et al. [12] Study describes the economic analysis of a stand-alone hybrid energy system for application in Iran and reveals that the wind hydrogen-battery hybrid system is the most economical one with a COE of US\$ 0.783/kWh. Shezan et al. [13] performed techno-economic analysis of a smart grid hybrid renewable energy system for Brisbane city of Australia and observed that the PV-wind-diesel-battery hybrid system is the most optimal among all other hybrid systems.

Khalid et al. [14] presented a thermo-economic analysis of a solar-biomass integrated multigenerational system and identified that the solar-biomass integrated system is more efficient and economic compared to the cases where solar and biomass systems are running individually. Lao et al. [15] performed a techno-economic analysis of a hybrid system using a diesel genset, PV, and battery with different combinations and revealed that the diesel/PV battery system is the optimal solution. Halabi et al. [16] analysed the performance of a hybrid PV/diesel/battery system, and results showed more trends towards using renewable sources in the energy generation and less dependence on standalone diesel generators. Usman et al. [17] performed the techno-economic analysis of a hybrid solar-diesel-grid connected power generation system and identified that the PV-grid connected system is found to be more economical with the lowest COE of ₹ 8.84/kWh. Habib Muhammad Usman et al. [18] This study investigates how an optimizing a hybrid microgrid combining wind turbines, solar photovoltaic (PV) systems, and grid integration to provide reliable and cost-effective energy to Chittorgarh, a village in India. The microgrid comprises a 165,024-kw wind turbine system and a 1,500-kw solar PV system, collectively generating 58,772,300 kWh annually. The economic analysis finds total initial capital of \$8.6 million, with a Cost of Energy (COE) of \$0.0413/kWh. After the techno-economic analysis, a sensitivity analysis is performed under varying conditions such as solar irradiance, fuel price,

energy production, and grid price variations to evaluate the system's robustness, adaptability, and economic feasibility. Most of the above studies are related to educational institutes, villages, and energy centres; however, there is a notable research gap in the techno-economic assessment of hybrid renewable energy systems specifically tailored for the healthcare sector. Hence, the present work focused on design and optimisation, sensitivity analysis of a hybrid renewable energy system for supplying the energy demand to the Healthcare centre at Srungavarapukota, Vizianagaram district of Andhra Pradesh in India. Six hybrid energy systems are designed and analysed using HOMER Pro to meet the healthcare centre's energy demand. A comparative study based on NPC and COE is carried out to identify the optimal configuration, followed by sensitivity analysis using different parameters to evaluate system performance.

2. Energy assessment at the location

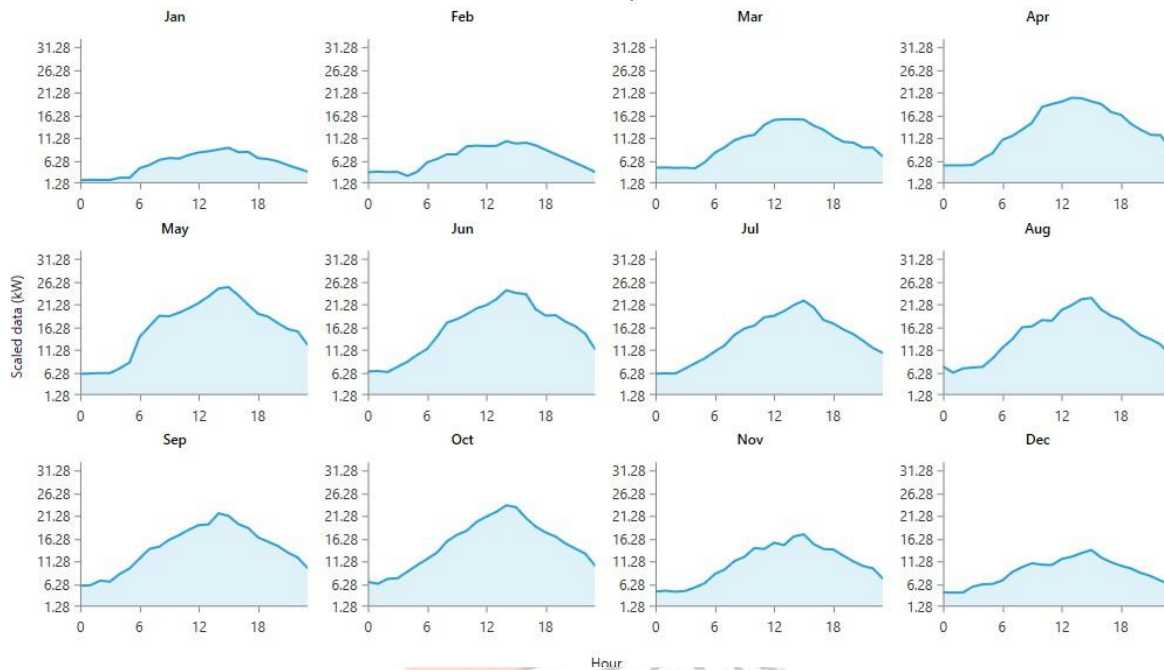


Fig.1: Primary load profile of the health centre

The Area Health Centre is in the rural village of Srungavarapukota, in the Vizianagaram district of Andhra Pradesh in India. The AHC has a primary load of 290.25 kWh/day with a peak load of 33.12 kW. The primary load demands are the electrical loads that the hybrid system is capable of meeting at any time. The Primary load profile is shown in Fig. 1. It is estimated that the maximum energy requirement occurs between 9:00 am to 6:00 pm in all months, with May showing the highest demand. This is because, during these hours, all the medical equipment, lighting loads, electrical fans, and air conditioners of the hospital consume most of the electrical energy.

2.1 Solar energy data:

The annual average solar irradiance and temperature at a specified location are taken from the National Aeronautics and Space Administration (NASA) resource website [19]. The available yearly average of solar radiation at the location is 5.06 kWh/m²/day. The monthly average solar radiation and clearness index are shown in Fig. 3. The annual average temperature at the location is approximately 27.5°C. The monthly average temperature is shown in Fig. 2.

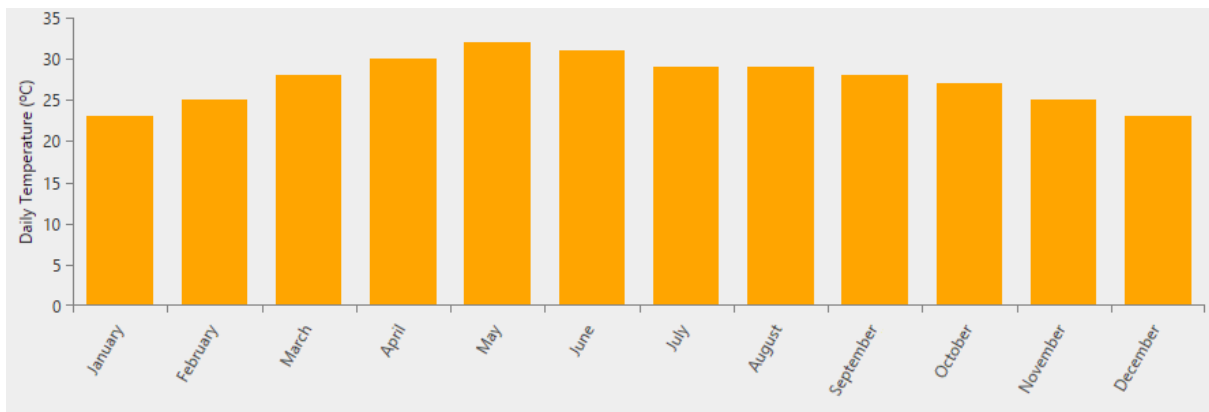


Fig.2: Monthly average temperature data at the health centre location

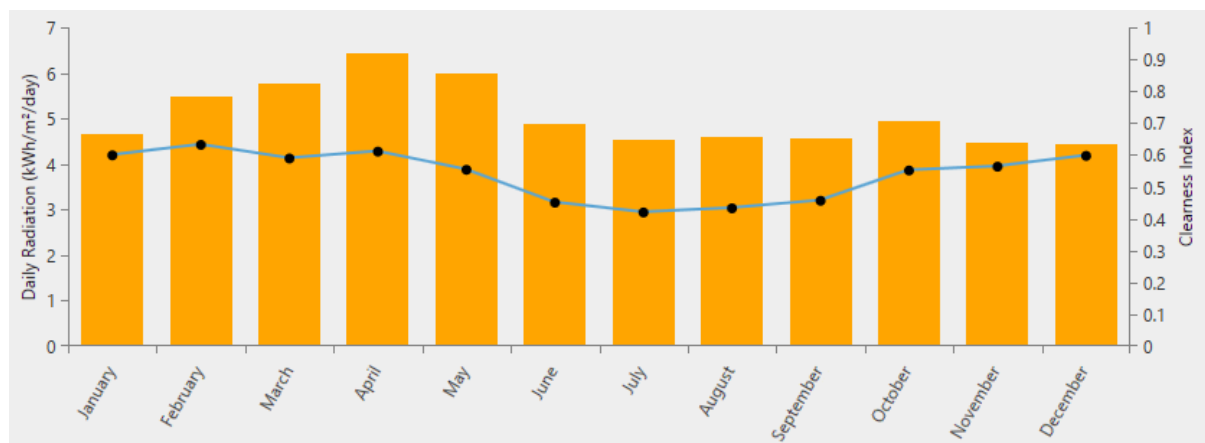


Fig.3: Monthly average solar radiation and clearness index at the health centre location.

2.2 Biomass data:

The biomass substances, like rice husk and vegetable waste, are considered due to their maximum availability in Andhra Pradesh. The available biomass data at the location of the health centre is taken from the Andhra Pradesh biomass website [20]. The annual average biomass available at the location is 46.56 tonnes per day. The monthly average biomass data is shown in Fig. 4.

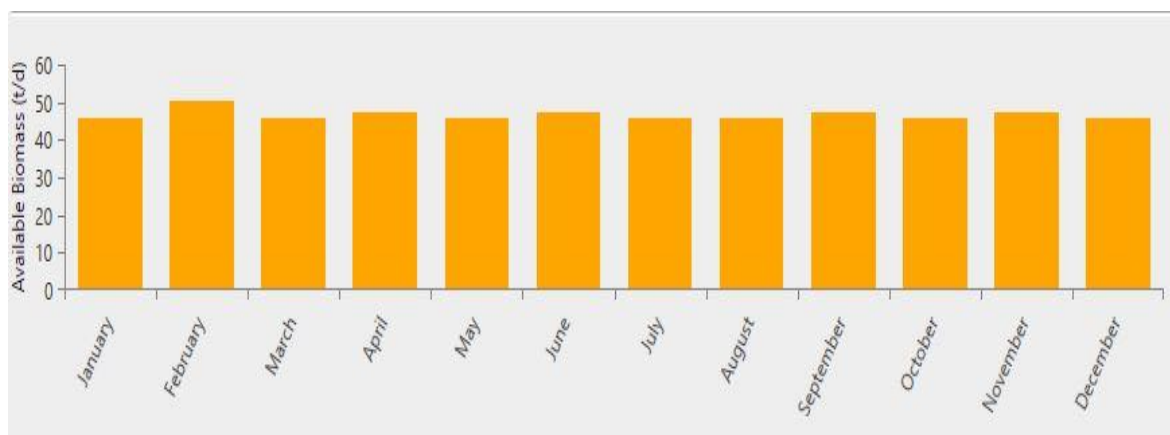


Fig.4: Monthly average biomass at the industry location

3. METHODOLOGY

The present section outlines the procedure followed for the design and optimization of hybrid renewable energy systems to meet the energy requirements of the healthcare centre. For this study, the HOMER Pro tool was used to model and optimize various hybrid systems. The complete methodology adopted in the study is illustrated in Fig.6.

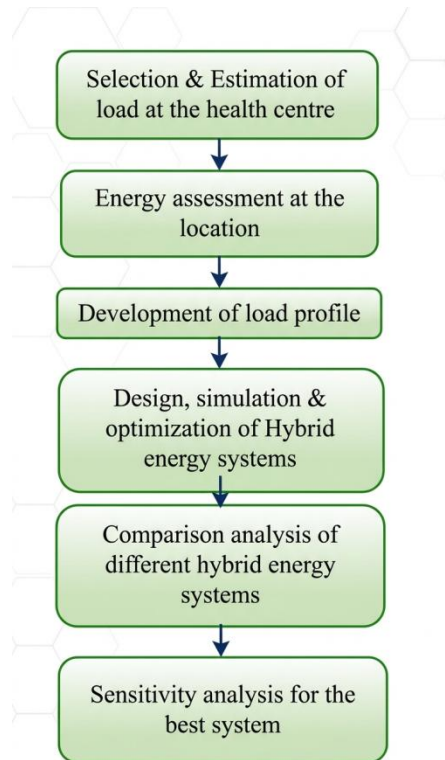


Fig.6: Methodology

Initially, a load assessment was carried out for the healthcare centre, and a corresponding load profile was developed and analysed using the data collected from the health care centre. The renewable energy potential at the site was evaluated using meteorological data provided by NASA. The technical and economic specifications required for the system design were gathered. Six different hybrid energy systems were designed and simulated using HOMER Pro. After identifying the most suitable hybrid system through simulations, performance evaluation was conducted based on the total lifecycle cost. Finally, a sensitivity analysis was performed for the best system.

3.1 Economic and technical specifications

The technical and economic specifications of each component in the hybrid system were discussed below.

3.1.1 Solar panel:

Solar energy is a primary renewable energy source. Solar panels use semiconductor-based photovoltaic (PV) cells to convert sunlight directly into electricity. They operate only during daytime conditions. In this study, 1.08 kW Waaree Energies monocrystalline silicon solar panels are considered [21].

Table1. Technical and economic specifications of solar panel

Parameters	Values
Cost of panel	\$ 283
Type of panel	Mono-crystalline PERC Panel
Material type	Mono-crystalline Silicon
Operational and Maintenance cost	\$ 5.65/year
Module efficiency	20.95%
Lifetime	27 years

3.1.2 Battery:

Batteries are used to store excess electrical energy generated by the PV panel during the day and supply power whenever there is a shortage of power during nighttime. An LRSA Lithium-ion battery of 12 volts, 100Ah is chosen for this work [22]. The specifications of the battery are shown in Table 2.

Table 2: Technical and economic specifications of the Battery

Parameters	Values
Type of battery	Lithium-ion
Capacity	100Ah
Volts	12V
Cost	\$ 198.9/unit
Replacement cost	\$ 198.9
Operational and Maintenance Cost	\$ 1.76/year
Life time	2500 cycles

3.1.3 Converter:

The converter is used to convert AC/DC to DC/AC electricity. The technical and economic specifications of the converter are shown in Table 3.2. Sofar converter of 3kW is considered for this study. The Nominal Power Output of the converter has a 3-kw capacity, making it suitable for small to medium-scale energy applications. The efficiency of the Sofar converter is remarkably high at 97.7%, making it a reliable choice for the system.

Table 3: Technical and economic specifications of the converter [23]

Parameters	Values
Cost	\$ 222.3
Replacement cost	\$ 222.3
Operational and maintenance costs	\$ 9.17/year
Efficiency	97.7%
Lifetime	10 years

3.1.4 Biomass generator:

A biomass generator is used to generate electricity with the help of biomass resources. The cost of energy depends on the cost of biomass fuel used. The technical and economic specifications of the biomass generator are shown in Table 4. A biomass generator of 12kW capacity with rice husk as feed material is considered for this study.

Table 4 Technical and economic specifications of biomass generator [24]

Parameters	Values
Cost	\$ 16965
Replacement cost	\$ 16965
Operational and maintenance costs	\$0.023/ hour
Lifetime	50000 hours

3.1.5 Grid:

The local grid is connected to the system to obtain a continuous power supply to the selected health centre. The electricity is purchased from the grid when there is a shortage and sold to the grid when there is excess. The cost of electricity purchased by the health centre from APEPDCL is \$ 0.18/kWh [25]. The excess energy generated by the hybrid energy system is sold to the grid at the sellback price of \$0.053/kWh.

3.1.6 System economics and constraints:

The project lifetime is considered as 25 years. The inflation rate and discount rate of 2% and 10%, respectively, are considered. The annual capacity shortage is taken as 0%, and the variation of load day-to-day is considered as 10%. The time step size is taken as 60 minutes. [26].

3.2 Design of different hybrid energy systems

Six different hybrid energy system configurations were designed using the technical and economic specifications of system components. Among these, three configurations are grid-connected systems, two are standalone systems, and one is a standalone hybrid system. The designed configurations are as follows:

- **Case 1:** Standalone PV system
- **Case 2:** PV-grid connected hybrid energy system
- **Case 3:** Standalone biomass system
- **Case 4:** Biomass-grid connected hybrid energy system
- **Case 5:** PV-biomass hybrid energy system
- **Case 6:** PV-biomass-grid connected hybrid energy system

A detailed description of each configuration is presented in the following subsections.

3.2.1 CASE 1:

In this case, a standalone PV system is designed to meet the energy demand of the health centre, as shown in Fig. 7. The system consists of solar panels, a battery, and a converter. Solar panels generate electricity during daytime, while excess energy is stored in the battery for use during night time or cloudy conditions.

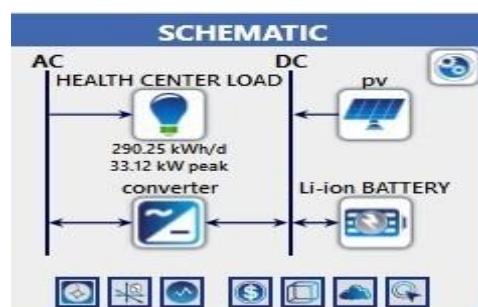


Fig.7: Standalone PV system with battery

3.2.2 CASE 2:

This configuration is similar to the standalone PV system with added grid connectivity. Solar PV supplies the load during daytime, while excess energy is exported to the grid through net metering. During low solar generation or nighttime, power is imported from the grid. Fig. 8 shows the schematic diagram of the PV-grid hybrid system.

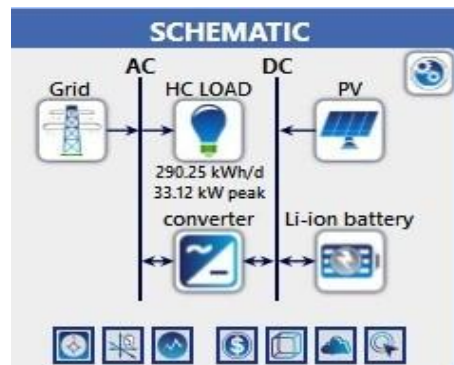


Fig.8: PV-grid connected system with battery

3.2.3 CASE 3:

This schematic consists of a standalone biomass system with the battery as a storage component. The design for this system is shown on Fig. 9. Biomass like rice husk, which is available on average of 46.56 tons per day with the price of Rs 5500 per ton, is considered [63]. The demand is supplied by the renewable biomass generator, and the excess is stored by the battery and supplies whenever required.

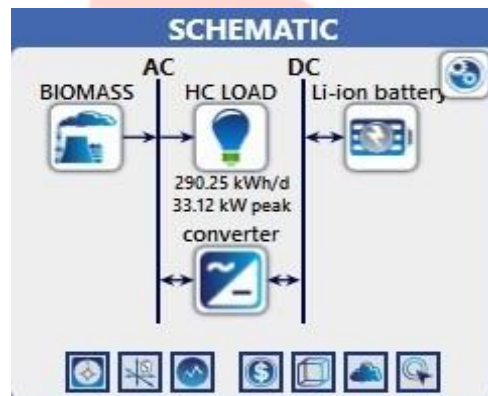


Fig.9: Stand-alone Biomass system

3.2.4 CASE 4:

This schematic comprises a Biomass system connected to the local grid. The design of the system is shown in Fig.10. The primary source for electricity generation is provided by a biomass system, and when there is a shortage in fuel supply, energy is purchased from the grid at the given price.

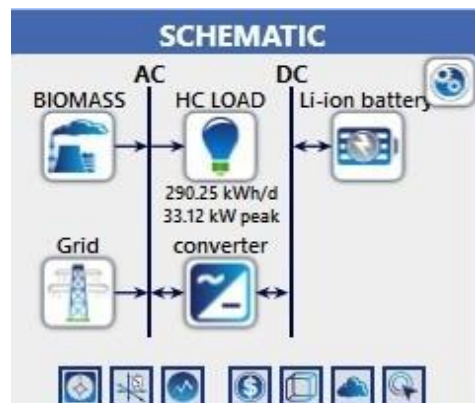


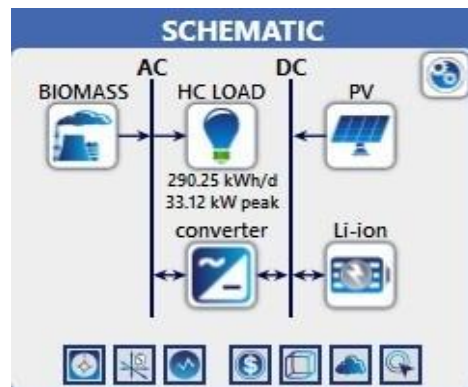
Fig.10: Biomass-grid connected hybrid system

3.2.5 CASE 5:

In this case, the integrated solar biomass system is considered with a battery and a Converter. The design for the system is shown in Fig.11. The primary renewable sources such as solar and biomass, is taken. The biomass generator supplies the demand whenever the load does not meet with PV arrays during cloudy days or nights, if necessary. If excess energy is generated, that part is stored in the battery with the help of a converter, which converts DC into AC electricity.

3.2.6 CASE 6:

In this hybrid model, the PV-biomass-grid connected system is considered. The design of the system is shown in Fig.12. The excess energy is generated by both biomass and PV arrays is sold to the grid to reduce the payback period. During cloudy days or nights, the biomass generator or



grid supplies the demand needed by the health centre. Batteries are also used for storing excess electricity.

Fig.11: PV-Biomass hybrid energy system

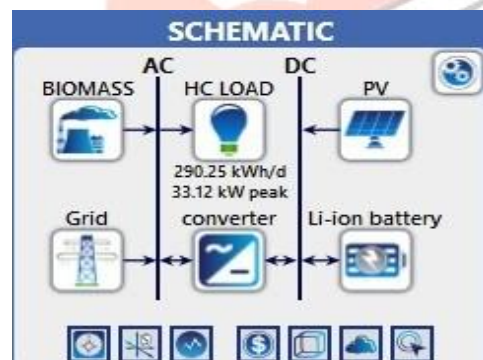


Fig.12: PV-Biomass-grid connected hybrid system

3.3 Optimization procedure of the hybrid energy system:

HOMER (Hybrid Optimization Model for Electric Renewables) is a software tool developed by the U.S. National Renewable Energy Laboratory (NREL) for designing and evaluating micro power systems. It enables users to compare different power generation technologies for a wide range of applications. HOMER performs three main functions: simulation, optimization, and sensitivity analysis. It is a comprehensive platform for designing, modelling, and analysing renewable energy systems, helping to determine the optimal configuration, size, and control strategies for hybrid power systems.

The software can model both grid-connected and off-grid systems that serve electrical and thermal loads. It works with a variety of energy sources and components, including photovoltaic (PV) modules, wind turbines, small hydro systems, biomass power, reciprocating engine generators, micro turbines, fuel cells, batteries, and hydrogen storage. HOMER allows users to perform

comparative economic and performance analyses of different hybrid energy systems to identify the most cost-effective and efficient solution in terms of size, structure, and performance. Its goal is to implement a hybrid system that is both environmentally friendly and capable of reliably meeting energy demands at the lowest possible cost.

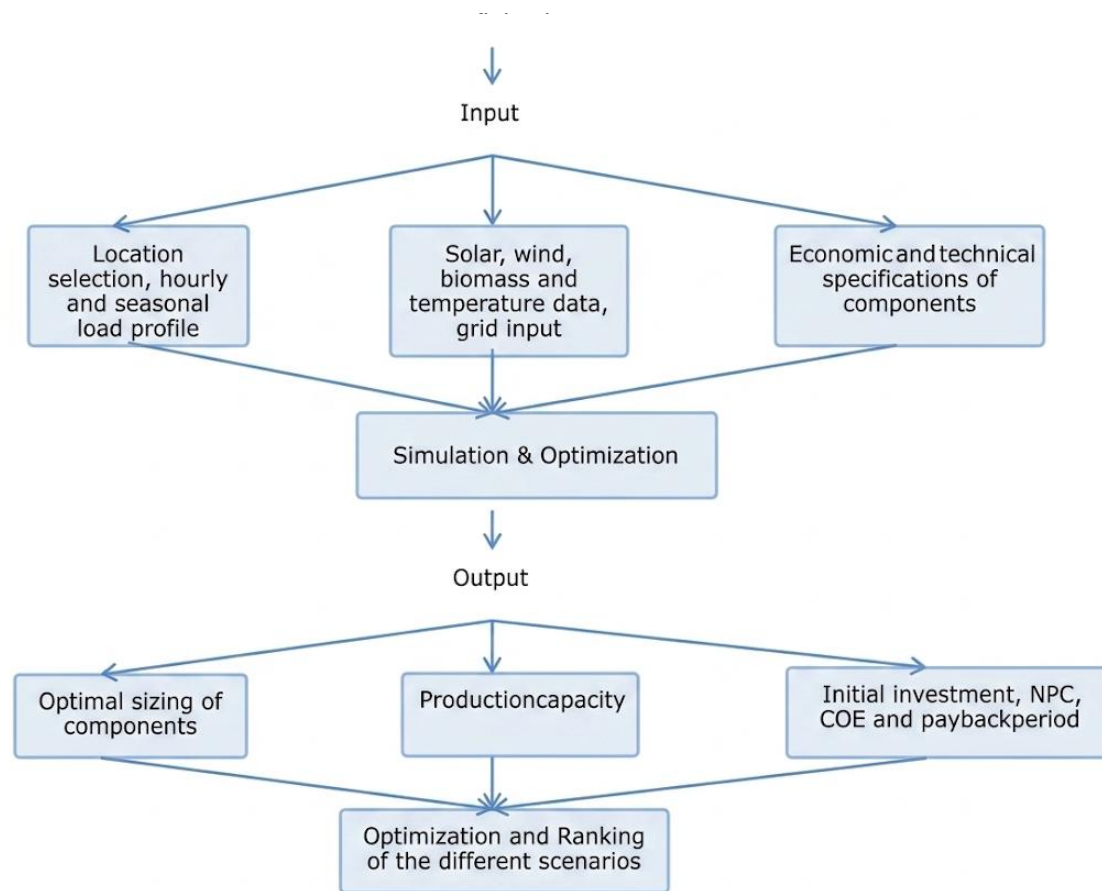


Fig.13: Optimization procedure

Simulation in HOMER involves representing the performance of a power system or process. It can simulate a wide range of micro power systems that may include PV arrays, wind turbines, run-of-river hydro turbines, generators, battery banks, DC-AC converters, electrolyzers, and hydrogen storage tanks. The simulation involves two main steps: first, it checks whether a proposed system can meet all electrical and thermal demands, along with any user-defined constraints. Second, it calculates the system life-cycle cost, which includes total installation and operational costs over the system's lifespan.

The optimization process, illustrated in Fig. 13, builds models and identifies the configuration with the lowest lifecycle cost. Key input data include project location, hourly and seasonal load profiles, energy resource data (e.g., solar radiation, wind speed, biomass availability, and temperature), as well as technical and economic specifications of system components.

The Net Present Cost (NPC), which includes initial investment, component replacement, maintenance, and the cost of purchasing electricity from the grid, is used as a measure of lifecycle cost. Revenues, such as income from selling power to the grid and any salvage value at the end of the project's lifetime, are also factored into the analysis.

3.4 ECONOMIC MODELLING:

Economics play a crucial role in both the simulation and optimization processes within HOMER. During the simulation phase, the software operates the system in a way that aims to minimize the total Net Present Cost (NPC). In the optimization phase, it evaluates various system configurations to identify the one with the lowest NPC. The NPC represents the system's life cycle cost, which includes the initial capital investment, cost of component replacements, maintenance

expenses, and the cost of electricity purchased from the grid. On the other hand, revenues are considered from selling excess electricity to the grid and any salvage value of components remaining at the end of the project's lifespan.

To determine the salvage value of each component at the end of the project lifetime, HOMER uses Equation 1 [6].

$$S = C_{\text{rep}} \frac{R_{\text{rem}}}{R_{\text{comp}}} \quad (1)$$

where S is the salvage value, C_{rep} is the replacement cost of the component, R_{rem} is the remaining life of component and R_{comp} is the lifetime of the component.

The annualized cost describes the combined capital, replacement, maintenance and fuel costs with salvage value and other revenues of each component. Levelized cost of energy (LCOE) is the average cost per kilowatt-hour of useful energy that is generated by the system. HOMER calculates total NPC and LCOE using total annualized cost of the system.

HOMER uses the given equation 2 [6] to calculate the total NPC,

$$C_{\text{NPC}} = \frac{C_{\text{TA}}}{\text{CRF}} \quad (2)$$

where C_{TA} is the total annualized cost, CRF is the capital recovery factor, given by equation 3 [6].

$$\text{CRF} = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (3)$$

where i is the annual real interest rate and N is the number of years.

HOMER uses the following equation 4[6] to calculate the levelized cost of energy,

$$\text{COE} = \frac{C_{\text{TA}}}{E_p + E_d + E_{\text{gs}}} \quad (4)$$

where C_{TA} is the total annualized cost, E_p is the total primary electrical load, E_d is the total deferrable load, and E_{gs} is the amount of energy sold to the grid per year.

The payback period is the number of years to recover the initial investment and is determined by equation 5 [6].

$$\text{Payback period} = \frac{\text{Total initial capital}}{\text{cost of energy saving per year}} \quad (5)$$

4. RESULTS AND DISCUSSIONS:

The simulations are carried out for all 6 cases are carried out using Homer Pro. The optimal solution of each case is then identified based on net present cost(NPC). A detailed discussion of the optimization and economics results is presented in the following subsections.

4.1 CASE 1:

Table 5 represents the optimization results of a standalone PV system. The results were generated using Homer Pro. it is found that the optimal system is a combination of solar panel of 299 kW and storage battery of 365 quantity, converter of 36.7 kW with a net present cost of \$ 1,79,269, levelized cost of energy \$ 0.157, operating cost of \$ 2,456 per year.

Table 5: Optimization results of Case 1

PV (kW)	Batteries (Qty)	Converter (kW)	COE (\$)	NPC (\$)	Ren Frac (%)
299	365	36.7	0.157	1,79,269	100

From Table 6, it is observed that the demand required for the health centre is met by the solar panel produces 4,79,971 kWh/yr. The battery is used to store the excess power and supplies

whenever required during nighttime or cloudy days. Table 6 depicts the electrical power generation by the PV, and its percentage is 100 due to a standalone PV system.

Table 6: Annual electricity production of Case 1 components

Production	kWh/yr	%
Waaree Solar-PV	4,79,971	100
Total	4,79,971	100

Fig. 14 represents the average electrical energy production from photo photovoltaic cell. Total energy produced by PV is 4,79,971 kWh annually, which is the total contribution from the system.

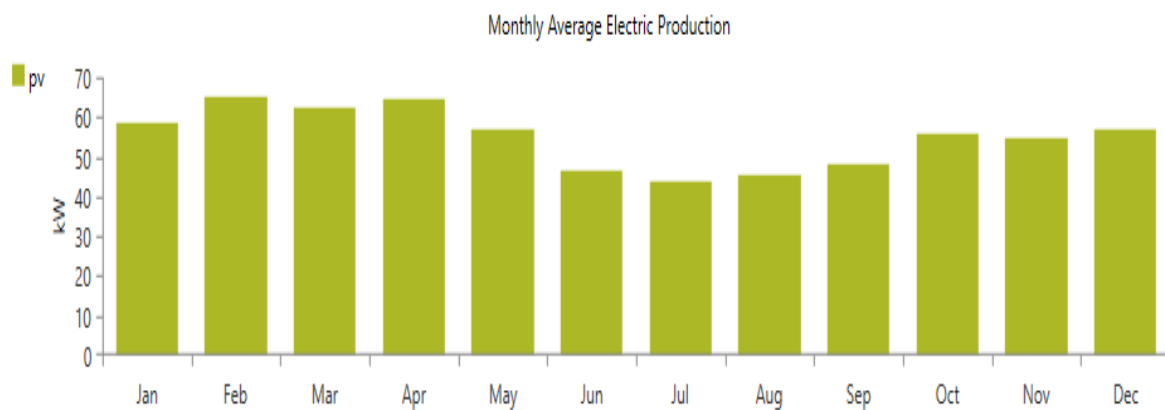


Fig.14: Monthly average electrical energy generated by components

A battery stores the energy from PV and discharges the energy in the absence of solar radiation. From Fig. 14, the electricity generated by the PV is higher in April as the radiation is high. The unmet electricity load is 3,69,135 kWh/year, which is 76.9 because solar energy resource is a seasonal dependent source in May, June, July, Aug, and Sep, the required energy production is very low, so the unmet load is higher. Table 7 shows the cost summary of case 1. The initial cost of the solar PV is more compared to the batteries. So, the initial cost is the maximum contribution in the Net present cost.

Table 7: Cost summary of the standalone PV system

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
SolarPV	77578.93	0.00	16782.32	0.00	0.00	94361.25
Battery	72412.35	0.00	6910.88	0.00	-3.26	79319.97
converter	2710.33	1872.44	1210.10	0.00	-205.20	5587.67
System	152701	1872.44	24903.30	0.00	-208.46	1,79,268.89

4.2 Case 2:

Table 8 shows the Optimization results of the PV-grid connected system. The optimization results were generated using HOMER Pro. The system consists of a solar panel, storage battery, converter, and a grid. The excess electricity is sold to the grid for \$ 0.053/kWh and purchased from the grid when there is a shortage for \$ 0.18 /kWh. The highest rank is given to the following configuration: PV85 kW and the converter of 67.2 kW, and the Grid based on the lifecycle

cost. Table 9 represents the average electrical energy production from solar-PV and purchased from the grid. Total energy produced by solar-PV is 1,36,224 kWh annually, which is the total contribution from the system. Excess electricity generated by the PV is sold to the grid. The PV power generation is about 72.9%, and grid purchases of 27.1%, and the unmet load is very less, 0%. Excess electricity is produced, 791 kWh/year. This system serves the AC primary load of 1,05,941 kWh/yr, which is about 57.9% of total generation, and 77,021 kWh/yr of electricity sold to the grid. From Fig. 15, the PV and Grid produce electricity monthly, and in June, PV production is more compared to other months, and Grid production is higher in January. Table 10 represents the cost summary of the components. The initial cost of the solar PV is \$ 22043, which contributes to the maximum percentage in the net present cost.

Table 8: Optimization results of Case 2

PV (kW)	Batteries (Qty)	Grid (kW)	Converter (kW)	COE (\$)	NPC (\$)	Ren Frac (%)
85	-	9,99,999	67.2	0.0148	29266	72.3
85	10	9,99,999	67.2	0.0157	31145	72.3
-	-	9,99,999	-	0.180	206319	0
-	10	9,99,999	15	0.184	210476	0

Table 9: Annual electricity production of Case 2 components

Production	kWh/yr	%
Waaree Solar-PV	1,36,224	72.9
Grid Purchases	50,644	27.1
Total	1,86,869	100

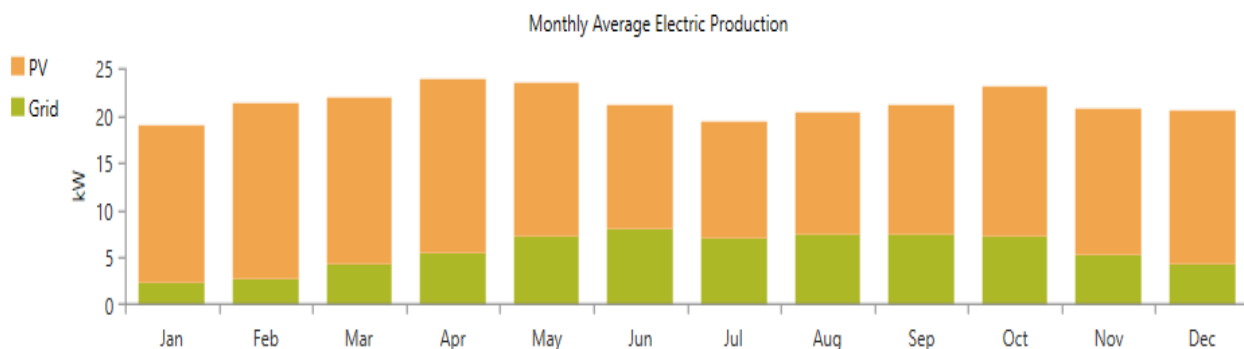


Fig.15: Monthly average electrical energy generated by components

Table 10: Cost summary of the PV-Grid connected hybrid system

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
SolarPV	22043.33	0.00	4768.53	0.00	0.00	26811.86
Grid	0.00	0.00	-7785.19	0.00	0.00	-7785.19
converter	4966.75	3431.29	2217.54	0.00	-376.04	10239.54
System	27010.08	3431.29	-799.11	0.00	-376.04	29266.22

4.3 CASE 3:

Table 11 shows the Optimization results of the standalone biomass system. The optimization results were generated using HOMER Pro. The system consists of a biomass generator, a storage battery, and a converter. The highest rank is given to the following configuration: biomass generator 30 kW, battery of 30 quantity, and converter of 8.85 kW based on lifecycle cost. Table 12 represents the average electrical energy production from the Biomass generator. Total energy produced by the biomass generator is 1,08,814 kWh annually, which is the total contribution from the system. Excess electricity generated by the biomass generator is stored in the battery. The Biomass generates power of about 100%, and the unmet load is zero. Excess electricity is produced, 0 kWh/year. This system serves the AC primary load of 1,05,941 kWh/yr. From Fig. 16, the biomass generator produces electricity monthly; in May, biomass production is more than in other months. Table 13 represents the cost summary of the components. The initial cost of the biomass generator is \$ 42303.75, and Fuel of \$ 140813.12, which contributes to the maximum percentage in the net present cost.

Table 11: Optimization results of Case 3

Biomass generator (kW)	Batteries (Qty)	Converter (kW)	COE (\$)	NPC (\$)	Ren Frac (%)
30	30	8.85	0.212	243285	100
40	-	-	0.247	282823	100

Table 12: Annual electricity production of Case 3 components

Production	kWh/yr	%
Biomass generator	1,08,814	100
Total	1,08,814	100

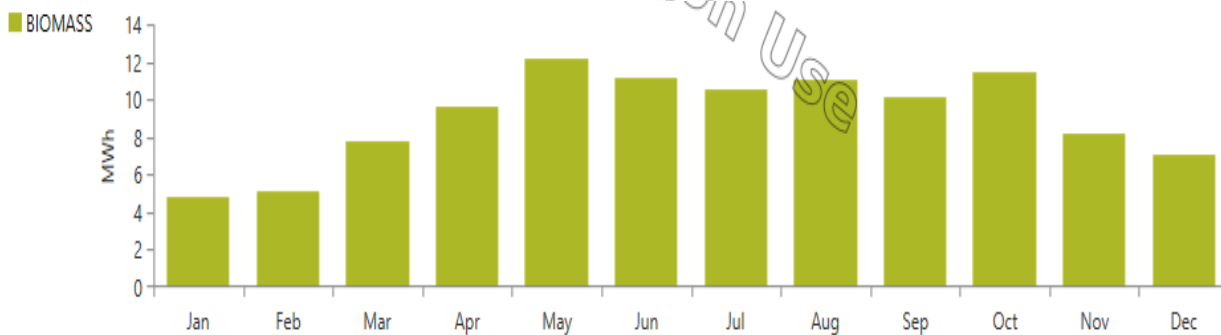


Fig.16: Monthly average electrical energy generated by components

Table 13: Cost summary of the Standalone Biomass

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
Biomass generator	42303.75	46524.88	4261.48	140813.12	-3683.27	230219.96
Battery	5951.70	5991.21	568.02	0.00	-794.28	11716.64
converter	654.10	451.89	292.02	0.00	-49.52	1348.48
System	48909.55	52967.97	5121.51	140813.12	-4527.08	243285.08

4.4 CASE 4:

Table 14 shows the Optimization results of the Biomass-Grid connected system. The optimization results were generated using HOMER Pro. The system consists of a biomass generator, a storage battery, and a converter. The highest rank is given to the following configuration: biomass generator 12 kW and Grid based on lifecycle cost. Table 15 represents the annual average electrical energy production from the Biomass generator and the Grid. Total energy produced by the biomass generator and grid is 77480 kWh and 28461 kWh annually. Excess electricity generated by the biomass generator is either stored in the battery or sold to the grid. The Biomass generates power of about 73.1%, and the unmet load is zero. Excess electricity is produced, 0 kWh/year. This system serves the AC primary load of 1,05,941 kWh/yr. From Fig. 17, the biomass generator produces electricity monthly, and the remaining produced by the Grid. In all months, production of biomass is not the same in May, it produces more, and the grid produces more energy in May. Table 16 represents the cost summary of the components. The initial cost of the biomass generator is \$ 16921, and the fuel cost of the biomass generator is \$99747.92, which contributes to the maximum percentage in the net present cost.

Table 14: Optimization results of Case 4

Biomass generator (kW)	Batteries (Qty)	Grid (kW)	Converter (kW)	COE (\$)	NPC (\$)	Ren Frac (%)
12	-	999999	-	0.168	192824	73.1
12	1	999999	15	0.170	195303	73.1
-	-	999999	-	0.18	206318	0
	1	999999	15	0.182	208797	0

Table 15: Annual average electricity production of Case 4 components

Production	kWh/yr	%
Biomass generator	77,480	73.1
Grid purchases	28,461	26.9
Total	105941	100

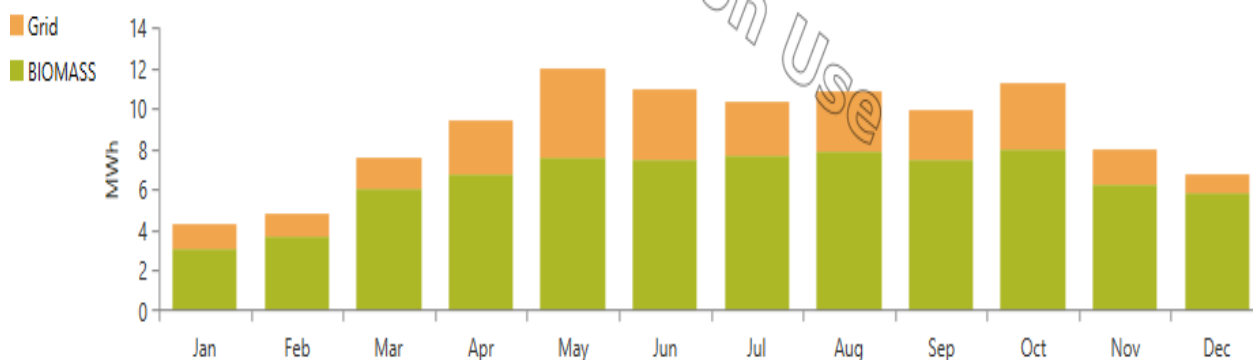


Fig.17: Monthly average electrical energy generated by components

Table 16: Cost summary of the Biomass-Grid hybrid system

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
Biomass generator	16921	19761.07	1824.29	99747.92	-857.06	137397.22
Grid	0.00	0.00	55,426.55	0.00	0.00	55426.55
System	16921	19761.07	57,250.83	99747.92	-857.06	192823.76

4.5 CASE 5:

Table 17 shows the Optimization results of the PV-biomasshybrid system. The optimization results were generated using HOMER Pro.

Table 17: Optimization results of Case 5

PV (kW)	Biomass generator (kW)	Batteries (Qty)	Converter (kW)	COE (\$)	NPC (\$)	Ren Frac (%)
91.6	24	149	29.5	0.117	133586	100
80	24	-	29.0	0.144	164596	100
-	24	80	15.0	0.203	232179	100
-	40	-	-	0.247	283176	100

The system consists of a solar PV, a biomass generator, a storage battery, and a converter. The highest rank is given to the following configuration: solar PV 91.6 kW biomass generator 24kW, Battery of 149 quantity, and converter 29.5 kW based on lifecycle cost.

Table 18 represents the annual average electrical energy production from the Biomass generator and the Grid. Total energy produced by the biomass generator and grid is 1,05,120 kWh and 22434 kWh annually. Excess electricity generated by the biomass generator is either stored in the battery or sold to the grid. The Biomass generates power of about 9.95%, and PV generates 90.5%, and the unmet load is zero. Excess electricity is produced, 53103 kWh/year. This system serves the AC primary load of 1,05,941 kWh/yr. From Fig. 18, the PV produces electricity maximum compared to the biomass generator, and the biomass generator produces electricity higher in the month of June, and the remaining maximum amount is produced by the PV. Table 19 represents the cost summary of the components. The initial cost of the biomass generator and Solar PV is \$ 33930 and \$2375, and the remaining battery and converter, which contributes to the maximum percentage in the net present cost.

Table 18: Annual average electricity production of Case 5 components

Production	kWh/yr	%
Solar PV	146802	90.1
Biomass Generator	16216	9.95
Total	163018	100

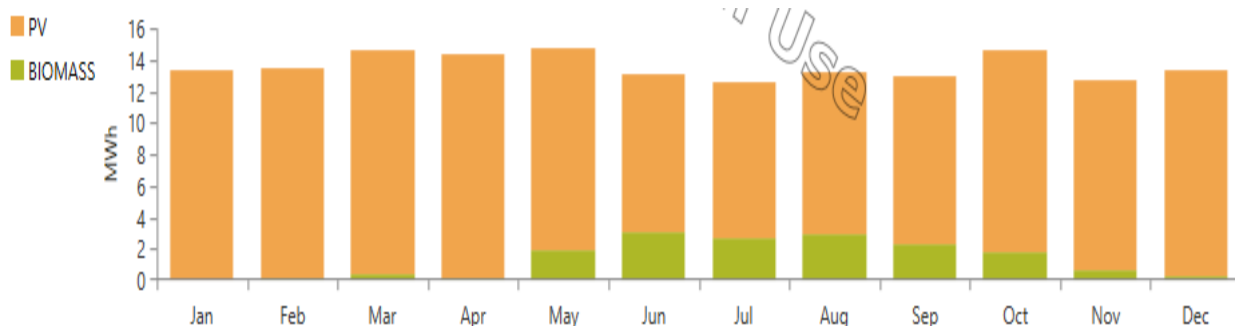


Fig.18: Monthly average electrical energy generated by components

Table 19: Cost summary of the PV-Biomass hybrid system

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
Biomass generator	33930.00	5345.96	1016.78	21147.76	-5027.27	56413.24
Solar PV	23754.93	0.00	5157.16	0.00	0.00	28912.09
Battery	29636.10	11394.36	2837.27	0.00	-112.96	43754.77
Converter	2185.95	1510.17	975.58	0.00	-165.50	4506.20
System	89506.98	18250.49	9986.80	21147.76	-5305.73	133586.31

4.6 CASE 6:

Table 20 shows the Optimization results of the PV-biomass-Grid hybrid system. The optimization results were generated using HOMER Pro.

Table 20: Optimization results of Case 6

PV (kW)	Biomass generator (kW)	Batteries (Qty)	Grid (kW)	Converter (kW)	COE (\$)	NPC (\$)	Ren Frac (%)
85	30	-	999999	65.2	0.0352	69499	79
85	30	1	999999	65.2	0.0353	69687	79
-	-	-	999999	-	0.180	206318	0
-	-	1	999999	15.0	0.182	208797	0

The system consists of a Solar PV, a biomass generator, a storage battery, a converter, and a grid. The highest rank is given to the following configuration: Solar PV 85 kW, biomass generator 30 kW, Converter of 65.2 kW, and Grid based on lifecycle cost. Table 21 represents the annual average electrical energy production from the Solar PV, Biomass generator, and the Grid. Total energy produced by the Solar PV, Biomass generator, and grid is 186868 kWh annually. Excess electricity generated by the Solar PV, biomass generator is either stored in the battery or sold to the grid. The Solar PV power of 72.9 % and Biomass generates power of about 6.61%, Grid purchases about 20.5%, and the unmet load is zero. Excess electricity is produced, 1295 kWh/year. This system serves the AC primary load of 1,05,941 kWh/yr and Grid sales of 76529 kWh/yr.

Table 21: Annual average electricity production of Case 6 components

Production	kWh/yr	%
Solar PV	136224	72.9
Biomass Generator	12345	6.61
Grid purchases	38,299	20.5
Total	186868	100

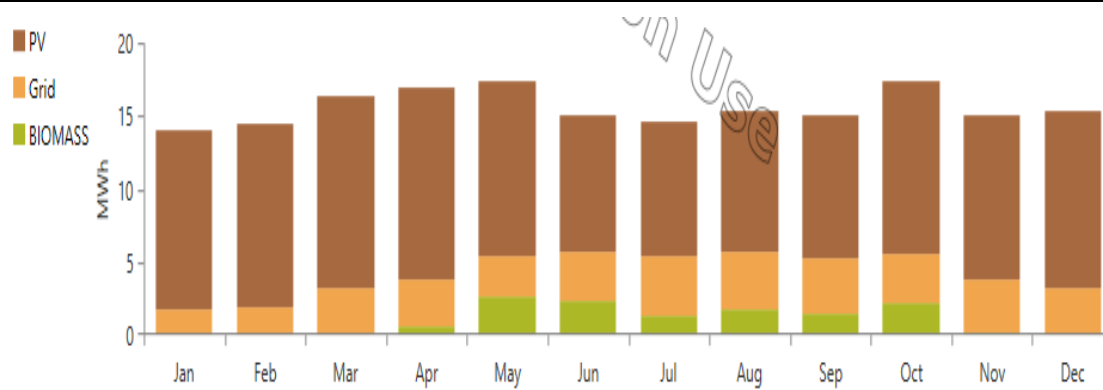


Fig.19: Monthly average electrical energy generated by components

From Fig. 19, the PV produces electricity maximum compared to the biomass generator, Grid, and the biomass generator produces electricity higher in the month of May, and the remaining maximum amount is produced by the PV. Table 22 represents the cost summary of the components. The initial cost of the biomass generator and Solar PV is \$ 43412.50 and \$ 22043 , and the remaining converter, which contributes to the maximum percentage in the net present cost.

Table 22: Cost summary of the PV-Biomass-Grid hybrid system

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
Biomass generator	42412.50	0.00	432.99	15954.28	-4187.25	54612.52
Solar PV	22043.33	0.00	4785.52	0.00	0.00	-21902.19
Grid	0.00	0.00	-21902.19	0.00	0.00	9959.46
Converter	4831.32	3337.73	2156.19	0.00	-365.78	26828.85
System	69287.15	3337.73	-14527.48	15954.28	-4553.03	69498.64

4.7 Comparative analysis of different hybrid energy systems:

The comparative analysis of different hybrid energy systems based on net present cost, cost of energy, and payback period is shown in Table 23.

Table 23: Comparative analysis of different hybrid energy systems

Hybridsystems	Initial capital(\$)	NPC (\$)	COE (\$)	Payback period(years)
Standalone PVsystem	152701	179269	0.157	15.25
PV-grid connected system	27010	29266	0.0148	1.40
Stand-alone biomass system	48909.55	243285	0.212	5.19
Biomass-grid connected system	16921	192824	0.168	3.71
PV-biomass hybrid system	89506.98	133586	0.117	3.62
PV-biomass-grid connected system	69287.15	69499	0.0352	3.66

It is observed that among all the other hybrid energy systems, the PV-grid connected system is the optimal system, which has the lowest NPC of \$29266, COE of \$0.0148, and payback period of 1.40 years among all scenarios. Electrical power is generated by PV during sunny days and utilizes the required power, and excess power generated is sold to the grid. When there is a shortage or during cloudy days, the electricity is purchased from the grid. The initial capital of the system is \$27010.

4.8 SYSTEM PERFORMANCE ASSESSMENT USING SENSITIVITY ANALYSIS

Sensitivity analysis is the process of changing the uncertain input variables to determine the effect of the uncertain variable on the system performance. The key sensitivity variables considered in this study are

- I. Variation of electric load
- II. Solar radiation
- III. Nominal discount rate
- IV. Derating factor
- V. Temperature
- VI. Efficiency of solar panel
- VII. Inflation
- VIII. Grid sellback price
- IX. Turning off net metering

4.8.1 Effect of electric load on cost parameters

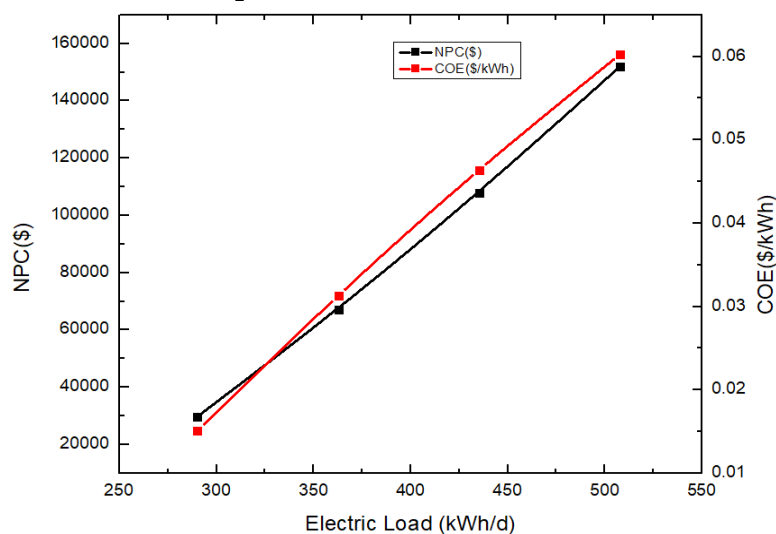


Fig.20: variation of electric load on cost parameter [28]

The sensitivity analysis of this system was conducted by varying the electric load by 125%, 150%, and 175% of the baseline load to assess impact of electric load variation on the Net Present Cost (NPC) and Cost of Energy (COE) in a PV-grid hybrid system. The analysis revealed notable trends in cost parameters in response to changes in electrical load. As depicted on Fig. 20, an increase in electrical load resulted in a corresponding rise in NPC and COE values. Additionally, the electrical load increased, which led to a decline in the renewable fraction as grid purchases increased and grid exports decreased. The sizes of the photovoltaic (PV) system (85 kW) and the converter (67.2 kW) remained unchanged despite variations in electric load, while grid dependence increased. These findings highlight the dynamic relationship between electrical load and cost parameters. Additionally, they demonstrate an inverse correlation between increasing load and renewable energy contribution in the system.

4.8.2 Solar radiation on cost parameters

Solar radiation significantly influences the electrical energy output of the PV system. To evaluate its impact, nine different solar radiation sensitivity values were analyzed using HOMER Pro. The variations in Cost of Energy (COE) and Net Present Cost (NPC) with respect to solar radiation are presented in Fig. 21. As the solar radiation increases from 4.8 to 6.4 kWh/m²/day, the COE decreases from \$0.019/kWh to \$0.00416/kWh, while the NPC reduces from \$36,422 to \$9,149. This reduction is mainly due to the increase in PV power generation, as shown in Fig. 22. Furthermore, higher solar radiation improves the renewable fraction, increases electricity export to

the grid, and decreases grid energy purchases, as illustrated in Fig. 23, thereby enhancing the overall economic performance of the system.

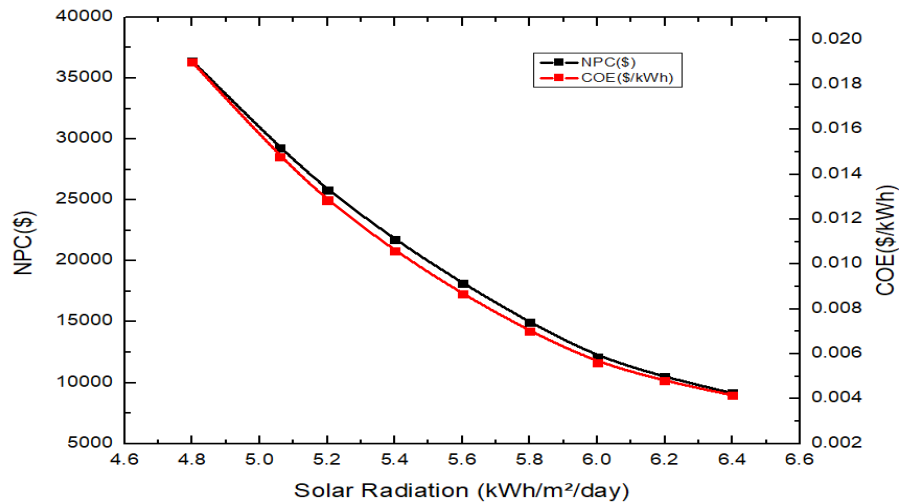


Fig.21: Impact of solar radiation on cost parameters

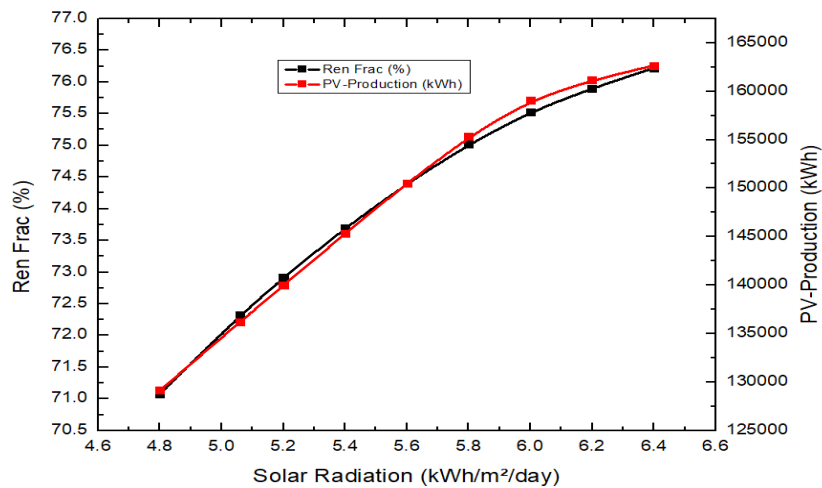


Fig.22: Impact of solar radiation on renewable Fraction and PV-Production(kWh)

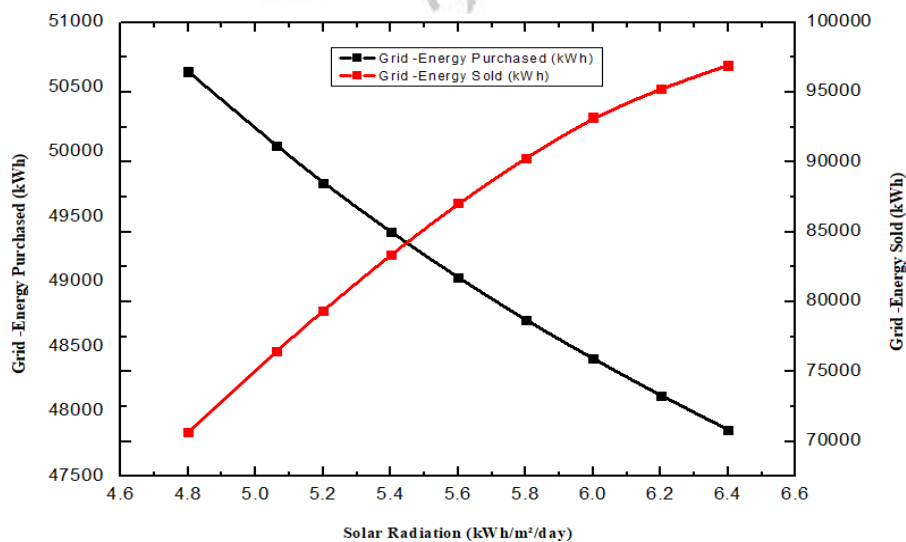


Fig.23: Effect of solar radiation on grid-energy purchases & grid-energy sold in (kWh)

4.8.3 Nominal discount rate on cost parameters

The nominal discount rate is very significant in economic evaluations and investment decisions. To comprehensively assess its impact on the cost parameters of optimized HRES, a sensitivity analysis is conducted using three different discount rates: 8%,9%,10%,11% and 12%. The findings, depicted in Fig 24, provide valuable insights into how variations in the nominal discount

rate influence the cost parameters. As the discount rate decreases from 12% to 8%, the NPC experiences a corresponding increase \$ 29848.18 to \$ 28804.23, while it decreases as the discount rate rises. This phenomenon occurred due to the time value of money; lower discount rates place greater emphasis on future cash flows, thus leading to higher present costs. On the other hand, a higher discount rates tends to emphasize present cash flows more ,which results in lower present value costs . The COE, on the other hand, exhibits an inverse relationship with the nominal discount rate. As the discount rate decreases, the COE decreases as well, and vice versa. This result mainly stems from how the discount rate influences the Levelized COE. When the discount rate is decreasing, the financing costs drop, which brings the COE down. On the other side, a higher discount rates makes financing more expensive, pushing the COE up. Based on these findings, it is evident that the choice of discount rate has a very powerful impact on the economic evaluation of renewable energy projects. The selection of correct discount rate is very crucial for the accurately assessing attractiveness of the investment opportunities.

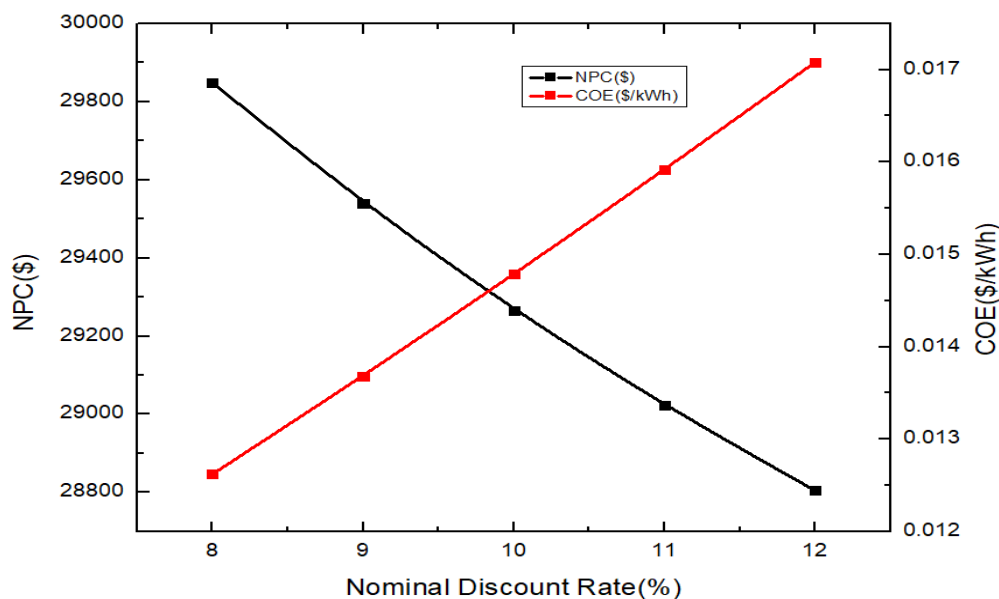


Fig.24: Impact of nominal discount rate on cost parameters. COE, cost of energy; NPC, net present cost.

A lower discount rate may be favorable when evaluating long-term and sustainable energy projects, as it values future benefits more highly and encourages the development of renewable energy infrastructure. Investors and policymakers must carefully select the discount rate based on project goals. A lower discount rate is more suitable for government-funded or long-term renewable energy projects where sustainability and energy security are prioritized over short-term returns. In contrast, private investors looking for quicker returns may prefer higher discount rates, as they reduce the present value of long-term expenses [66].

4.8.4 PV Derating Factor (%) on cost parameters & PV-production(kWh)

The variation of PV Derating Factor (%) plays a significant role in determining the electrical energy power output of the solar PV. so, to investigate this impact, four distinct Derating Factor (%) sensitivity values were input into the Homer Pro software, allowing for a comprehensive assessment of how PV Derating Factor (%) influences the cost parameters & Renewable fraction (%). The information regarding the PV Derating Factor (%), COE, and NPC is shown in the Fig. 25.

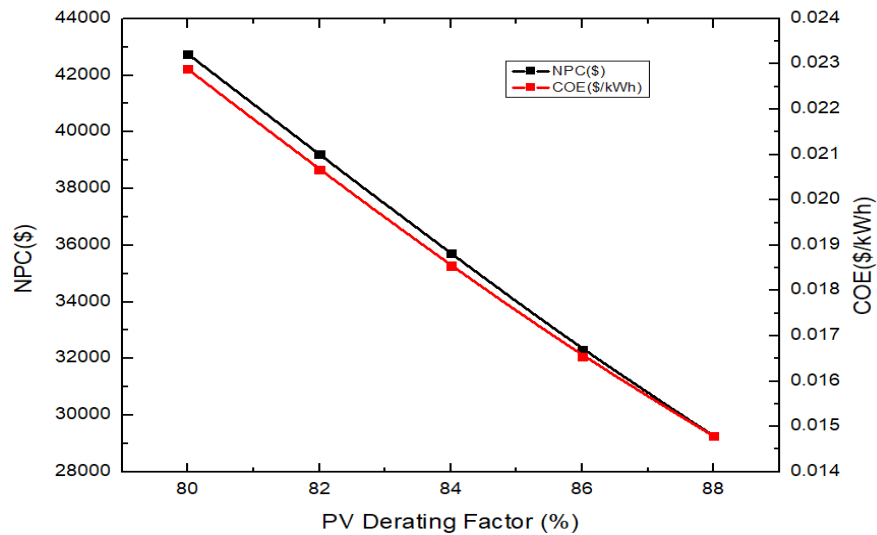


Fig.25: Impact of PV-Derating Factor (%) on cost parameters

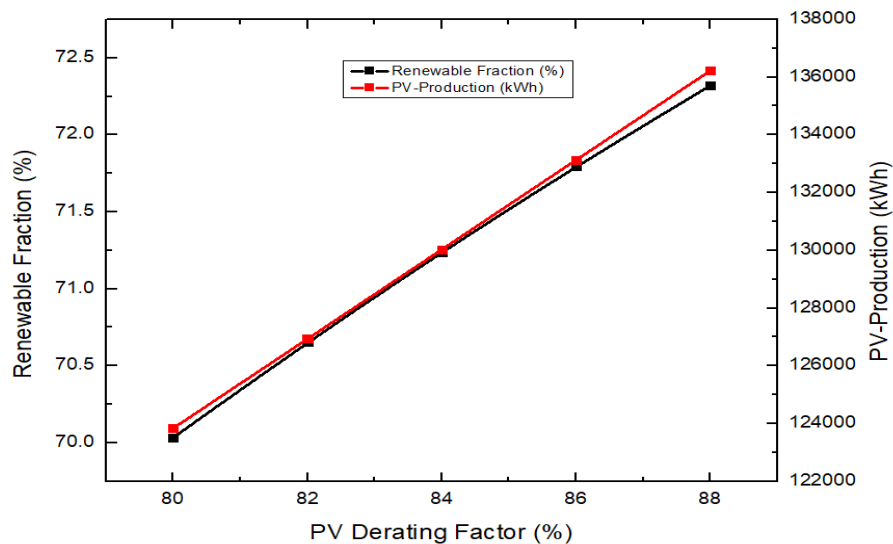


Fig.26: Impact of PV-Derating Factor (%) on Renewable Fraction (%) and PV- production (kWh)

As the Derating Factor (%) increases from 80% to 88%, a noticeable pattern emerges in both the COE and NPC columns. The COE decreases from 0.025 to 0.015\$/kWh, indicating a reduction in the COE. Simultaneously, the NPC decreases from \$ 42752.14 to \$ 29266.23, suggesting a decrease in the NPC. In terms of electricity production by PV Panel, increases with an increasing Derating Factor (%) are presented in Fig. 26. The decrease in NPC and COE is because Grid purchasing decreases, the electricity Production produced by PV increases because of the derating factor increases PV output, and the renewable fraction also increases.

4.8.5 Temperature (°C) on cost parameters and PV- Production (kWh)

The variation in the Temperature (°C) plays an important role in determining the electrical energy output from the solar PV system. To investigate this impact, four distinct temperature sensitivity values were input into the Homer Pro software, allowing for a comprehensive assessment of how temperature influences the cost parameters and PV-Production(kWh), renewable fraction(%). The information regarding temperature (°C), COE, and NPC is presented in a graphical format in Fig.27.

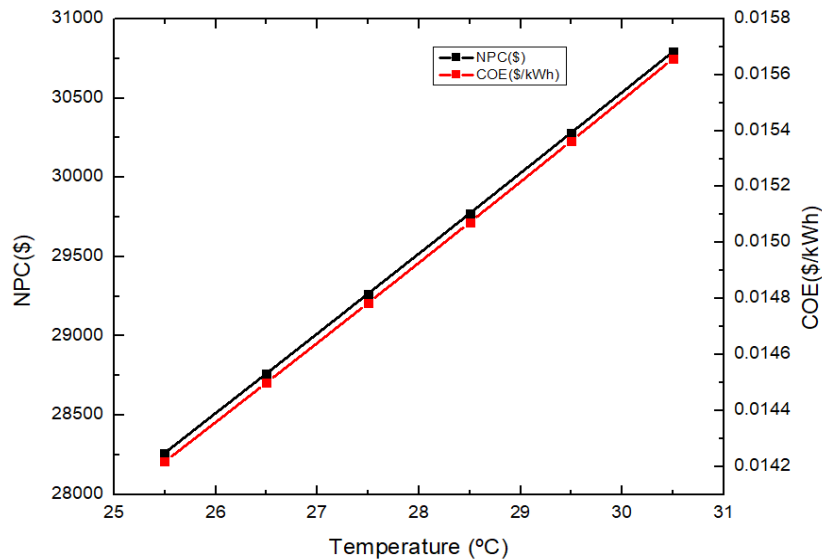


Fig.27: Effect of temperature (°C) on NPC and COE

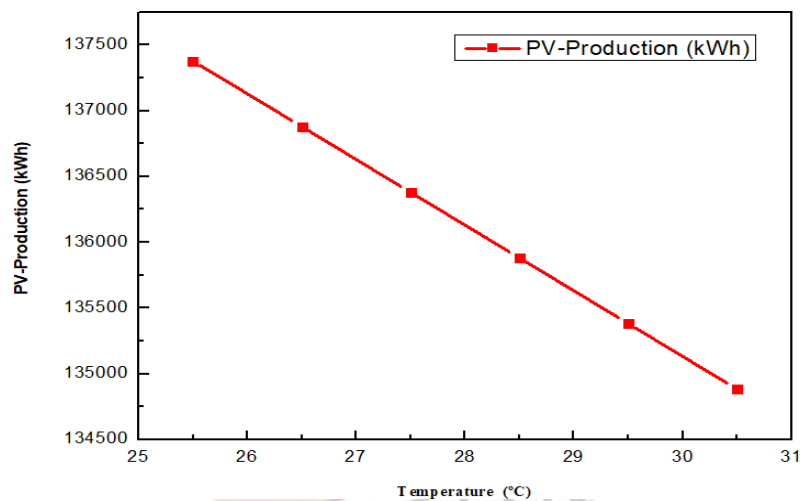


Fig.28: Effect of temperature (°C) on PV-Production(kWh)

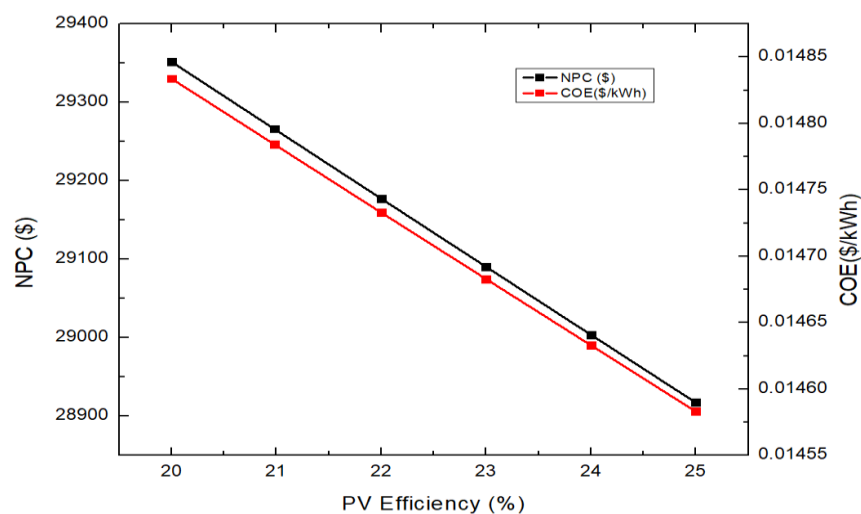


Fig.29:Effect of PV efficiency (%) on cost parameters

4.8.6 Efficiency on cost parameters and PV-Production (kWh): The variation in solar efficiency plays an important role in determining the electrical energy output from the solar PV system. To investigate this impact, six distinct efficiency sensitivity values were input into the Homer Pro software, allowing for a comprehensive assessment of how efficiency influences the

cost parameters, PV production, and renewable fraction. The information regarding efficiency, COE, and NPC is presented in a graphical format in Fig. 29. As efficiency increases from 20% to 25%, a noticeable pattern emerges in both the COE and NPC columns. The COE decreases from \$ 0.014784 to \$ 0.014583, indicating a reduction in the COE. Simultaneously, the NPC decreases from \$ 29266.23 to \$ 28917.36, suggesting a decrease in the NPC. In terms of electricity availability, interpreting results in Fig. 30 reveals that higher efficiency levels contribute to more PV production.

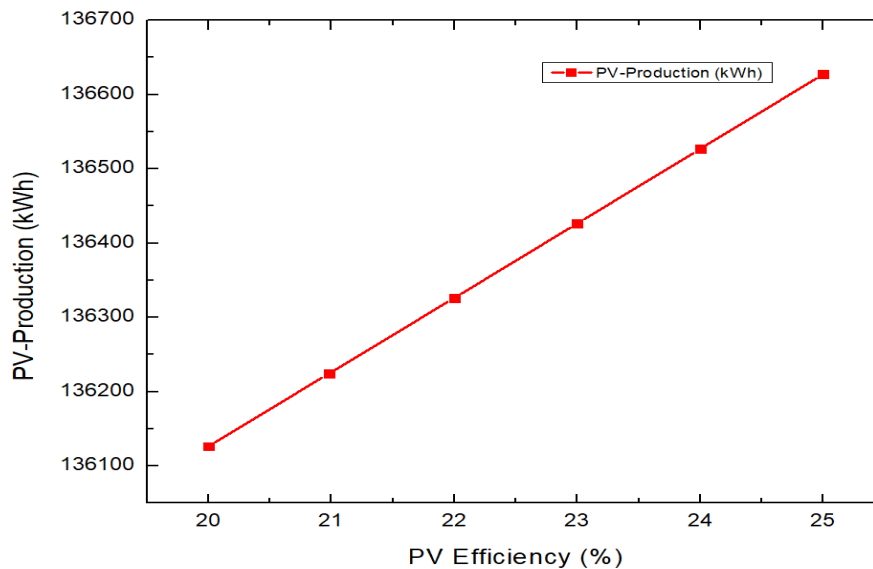


Fig.30:Effect of PV Efficiency (%) on PV Production(kWh)

4.8.7 INFLATION RATE (%) ON COST PARAMETERS

The inflation rate is very important in economic evaluations and investment decisions. To comprehensively assess its impact on the cost parameters of optimized HRES, a sensitivity analysis is conducted using five different inflation rates: 2%, 3%, 4%, 5%, and 6%. The findings, depicted in Fig. 31, provide valuable insights into how variations in the inflation rate influence the cost parameters.

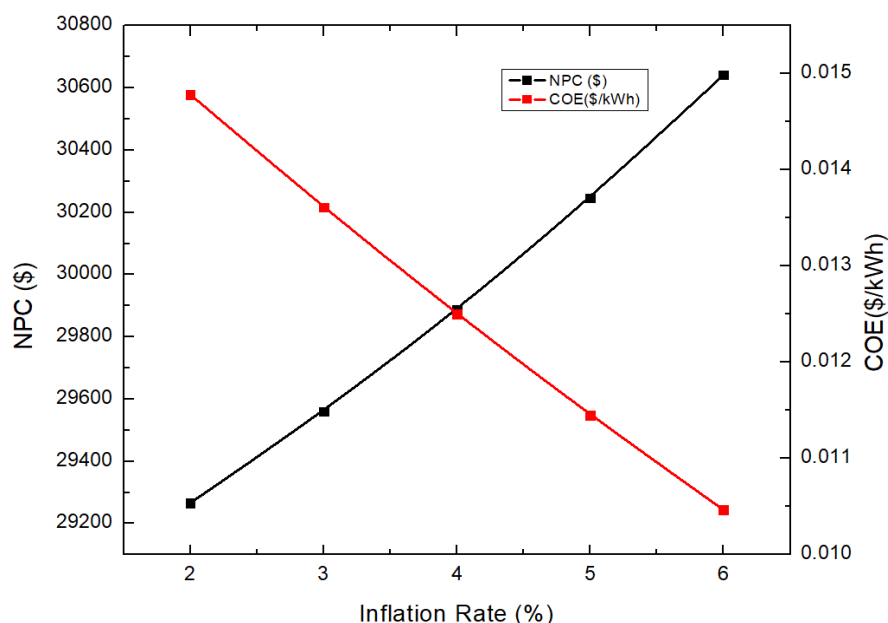


Fig.31: Effect of Inflation Rate (%) on Cost Parameters

As the inflation rate increases from 2% to 6%, the NPC experiences a corresponding increase from \$ 29266.23 to \$ 30641.46. Inflation raises future costs (O&M, replacements, fuel, etc.), which increases the overall system cost. As the inflation rate rises, the real discount rate decreases, meaning future costs are discounted less, making them appear higher in today's value. This leads to an increase in NPC because higher inflation results in higher present-valued costs and COE exhibits an inverse relationship with the inflation, as observed in Fig 31 , as the inflation rate increases from 2% to 6%, the COE experiences a corresponding decrease from \$0.014/kWh to \$0.010/kWh because COE is calculated based on the total energy generated over the system's lifetime. A higher inflation rate indicates that revenues increase over time because of electricity sales, which leads to a reduction in the overall cost of energy. As the inflation rate increases, the real discount rate decreases, which makes future revenues more valuable, which lowers the COE.

4.8.8 SELL BACK PRICE ON COST PARAMETERS:

The sell-back price of the grid plays an important role in the economic evaluation of the PV-grid hybrid energy system. To assess its influence on cost parameters, a sensitivity analysis was conducted by varying the sellback price from \$ 0.029/kWh to \$ 0.053/kWh. The results shown in Fig. 32 illustrate the relationship between the NPC and COE as the sell-back price changes. As the sell-back price increases, NPC and COE decrease because a higher sell-back price increases revenue from the excess electricity sold to the grid.

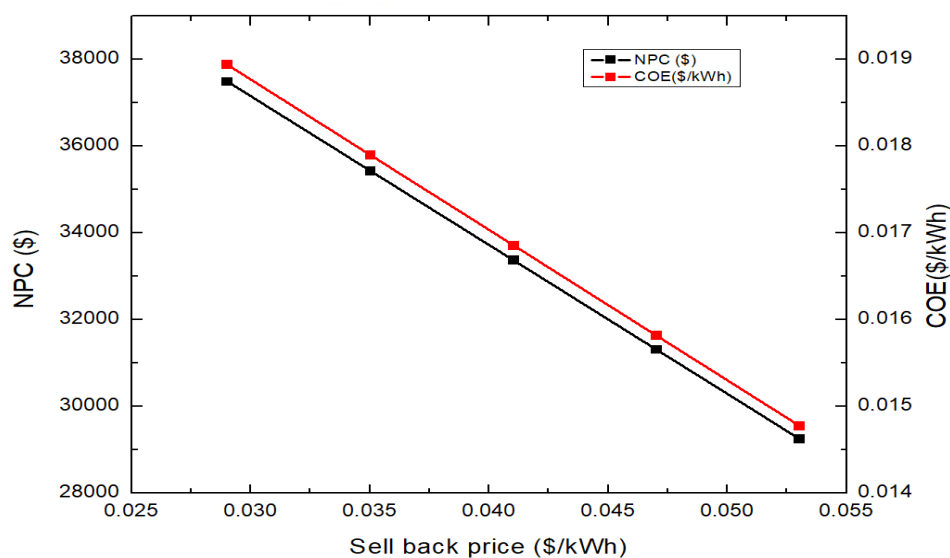


Fig.32: Effect of Grid sell-back price on cost parameters

4.8.9 EFFECT OF TURNING OFF NET METERING ON PV-GRID CONNECTED SYSTEM

From Table 24, the sensitivity analysis of the PV-Grid Hybrid Energy System with Net Metering Turned Off.

Table 24: Effect of turning off net metering on PV-Grid connected system

Sensitivity Analysis of PV-Grid Hybrid Energy System with Net Metering Turned Off				
PV (kW)	LI-ION BATTERIES (Qty)	GRID PURCHASE CAPACITY (kW)	CONVERTER (kW)	NPC (\$)
125	111	999999	90.80	63K
INITIAL COST (\$)	Renewable Fraction (%)	COE (\$/kWh)	PAYBACK (yr)	IRR (%)
61K	92.10	0.03	2.93	33.30

PRODUCTION			CONSUMPTION			QUANTITY		
Source	kWh/yr	%	Load/Item	kWh/yr.	%.	Item	kWh/yr..	%..
Grid Purchases	16549	7.63	AC Primary Load	105941	50.70	Capacity Shortage	0	0.00
Solar-PV	200330	92.40	Grid Sales	102828	49.30	Excess Electricity	1928	0.89
Total	216879	100.00	Total	102828	100.00	Unmet Electric Load	0	0.00

The system operates with 125 kW of solar PV, supported by 111 lithium-ion batteries and a 90.80 kW converter, achieving an impressive 92.10% renewable energy fraction. This reduces the dependency on the grid effectively, with only 16,549 kWh/year (7.63%) being purchased. The system produces a total of 216,879 kWh/year, of which 200,330 kWh/year (92.40%) comes from solar PV, while the remaining energy is sourced from grid purchases. despite generating surplus energy, 102,828 kWh/year (49.30%) was sold to the grid, which highly impacts the economics of the system. From a financial perspective, the system demonstrates strong profitability with a Net Present Cost (NPC) of \$ 63161, an initial cost of \$ 61149, and a Cost of Energy (COE) of \$ 0.03/kWh. By this system, the payback period of 2.93 years, which impacts the system performance and an Internal Rate of Return (IRR) of 33.30%, making it a profitable investment. The system also ensures uninterrupted energy supply with zero unmet load and no capacity shortage, indicating efficient load management. moreover, excess electricity generation accounts for 1,928 kWh/year (0.89%), which could be better utilized with optimized battery management or alternative energy storage strategies. With a high renewable fraction of 92.10%, the system is nearly self-sufficient, relying minimally on grid purchases (7.63%).

5. Conclusion

In this paper, Load Estimation & Energy Assessment for the Health Centre were estimated and calculated. Afterthat,six different hybrid energy systems, a standalone PV system, a PV-grid connected system, a standalone biomass system, a biomass-grid connected system, a PV-biomass system, and a PV-biomass grid connected system are simulated and optimizedfor the health centre which is inS. Kota, Vizianagaram district of Andhra Pradesh using HOMER Pro.The optimal hybrid energy system for the Health Centre is a PV-grid connected system. The system consists of: Solar PV: 85 kW Converter: 67.2 kW Economic Analysis like Net Present Cost (NPC) of \$ 29777, Cost of Energy (COE)of \$ 0.0151/kWh, Payback Period of 1.41 years.After comparing all the systems, the best one was identified. Sensitivity analysis was then performed to assess the impact of input parameters like Variation of electric load, Solar radiation, Nominal discount rate, Derating factor, Temperature, Efficiency of solar panel, Inflation, Grid sellback price, and turning off net metering on the system.

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