Sustainable Energy Solutions for Himachal Pradesh: A Comparative Study of Solar Panel Technologies

Mrinal Rawat[1] and Harpreet Kaur Channi[2,*]

[1]*Independent Research Scholar, Department of Electrical Engineering*

[2]*Department of Electrical Engineering, Guru Nanak Dev Engineering College, Ludhiana*

Abstract: The pursuit of sustainable energy solutions is critical in regions like Himachal Pradesh, India, where environmental preservation and energy access must go hand in hand. This study presents a comprehensive comparative analysis of two solar panel technologies—fixed tilted and two-axis rotating rooftop systems—under the state's on-grid rooftop solar scheme supported by central and state subsidies. Using detailed simulations in PVsyst, the research evaluates the systems' energy efficiency, economic feasibility, environmental implications, and policy alignment. Results show that while two-axis rotating panels offer moderately higher energy yield (6.23 kWh/day vs. 4.78 kWh/day), fixed tilted panels are economically more viable, exhibiting a shorter payback period (1.8 years vs. 2.3 years) and lower installation and maintenance costs. These findings endorse fixed tilted panels as a more cost-effective and sustainable solution for residential solar adoption in the region.

Keywords: PVsyst Software, On-grid System, Rooftop Solar Plant, Economic Analysis, Renewable Energy.

1. INTRODUCTION

The global shift toward renewable energy is no longer optional—it is imperative. Among the myriad alternatives, solar energy shines as a particularly promising solution due to its abundance, scalability, and decreasing cost. In ecologically sensitive regions like Himachal Pradesh, which is nestled within the Himalayan belt and renowned for its pristine environment, the balance between meeting growing energy demands and preserving ecological integrity is crucial [1]. Leveraging solar energy in such a setting represents not only a necessity but also a strategic imperative. The Government of Himachal Pradesh, in alignment with national objectives, has rolled out the Grid-Connected Rooftop Solar Scheme supported by central and state subsidies to catalyze solar adoption. However, the choice of solar panel technology significantly influences the effectiveness, cost-efficiency, and environmental impact of these systems. This study investigates two widely adopted rooftop configurations—fixed tilted and two-axis rotating solar panels—to determine which is better suited to the region's unique climatic and topographical context [2].Using PVsyst simulation software, this study evaluates and compares these technologies on key metrics: energy output, payback period, installation cost, performance ratio, and long-term return on investment. Previous studies have explored the general feasibility of solar systems in the Indian subcontinent using simulation tools like HOMER and PVsyst [3]. For instance, a 700 kW grid-connected solar plant simulated in Daikundi Province using PVsyst demonstrated a production of 1266 MWh/year with a performance ratio of 0.797, indicating good operational efficiency [4]. In a similar vein, hybrid systems have been optimized using TOPSIS to cater to rural household energy needs in Jammu and Kashmir. While these studies provide valuable insights, a focused comparative analysis of solar configurations specifically for Himachal Pradesh is still lacking. This study aims to fill that gap by offering empirical evidence to support policy decisions and stakeholder strategies. Through this analysis, we aspire to guide legislators, investors, and energy planners in making data-driven, regionally appropriate decisions that maximize solar potential while upholding ecological responsibilities.

2. LITERATURE SURVEY

Raghuwanshi *et al.*, 2019 described potential of RES and region-wise installed capacity in India. This includes performance optimization" (maintain consistency in spelling: use American or British English throughout) of solar pumping system and reliability assessments of the designed system using reliability indices [5]. Mukisa *et al.*, 2019 proposed an alternative approach to determination of rooftop area suitable for solar PV deployment by using validated open source tools that require minimal computational know-how [6]. Thotakura *et al.*, 2020 studied operational performance of megawatt-scale grid integrated rooftop solar pv system in tropical wet and dry climates of India. A framework is proposed to validate the existing simulation models that are used for PV project modeling. The solar PV plant supplied energy of 1325.42 MWh to the grid during the monitored period [7]. Hosseini *et al.*, 2020 discussed that the decentralization of electrical power generation using rooftop solar units is projected to develop to not only mitigate power losses along transmission and distribution lines, but to control greenhouse gases

*Address correspondence to this author at the Department of Electrical Engineering, Guru Nanak Dev Engineering College,Ludhiana;
E-mail: harpreetchanni@yahoo.in

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emissions. The feasibility of using hydrogen as a battery is analysed where hydrogen is produced by the extra diurnal generated electricity by a rooftop household solar power generation unit and utilized in a fuel cell system to generate the required electrical power at night. The feasibility of electricity production via solar energy in the Middle East is high due to the enormous value of solar radiation [8]. Al-Janahi *et al*., 2020 studied a novel bipv reconfiguration algorithm for maximum power generation under partial shading. The system is optimised for maximum yield to determine the optimal configuration and number of modules for each string using a genetic algorithm [9]. Pirmohamadi *et al*., 2021 studied integrated solar thermal systems in smart optimized zero energy buildings: energy, environment and economic assessments. An innovative energy optimization algorithm is employed for an existing office building. Apart from this optimization, an efficient solar thermal system is used for reducing building CO_2 emissions [10]. Jung *et al*., 2021 aimed to develop a geographic information system (GIS)-based reinforcement learning (RL) model for optimal planning of a rooftop PV system, considering the uncertainty of future scenarios throughout the life cycle of buildings. To that end, GIS was used to establish the spatial data for the rooftop PV installation, and an RL model was developed to maximize the economic profit of the rooftop PV installation in various locations and future scenarios [11]. Khare Saxena *et al*., 2021 examined simulation and energy analysis of a grid-tied 100 kW solar photovoltaic power plant mounted on an institute's building rooftop in Bhopal city of India are carried out. This study estimates the energy output, system losses and performance parameters for a 100 kW rooftop grid connected solar photovoltaic system. Utilizing rooftops as a solar power plant system on the grid can be an effective and efficient solution to reduce electricity bills [12]. Jaka *et al*., 2021 aimed to design and analyse the potential of 1215 Wp solar power plant rooftop with on grid system household scale in terms of techno economy [13]. Navothna *et al*., 2023 present a long-term performance analysis of a one-mega-watt power grid-connected PV plant installed on the rooftop of GITAM University, Visakhapatnam, Andhra Pradesh, India for 3 years. Solar irradiation data has been collected from the National Renewable Energy Laboratory (NREL) database for these years [14].

2.1. Problem Formulation

Himachal Pradesh must simultaneously fulfill the state's growing energy needs and protect its beautiful environment. The current rooftop solar program, which is supported by both federal and state government subsidies and is connected to the grid, requires careful consideration of two solar panel technologies: two-axis spinning panels and fixed tilted panels. A significant information vacuum is created by the absence of an extensive comparative research that is specific to the geographic and climatic characteristics of Himachal Pradesh. To maximize the sustainability and efficiency of rooftop solar installations in this area, legislators, investors, and solar project developers must close this gap in order to make well-informed decisions. The following are the main objectives:

- Analyse the feasibility analysis of solar PV system at the proposed Location, considering factors such as solar irradiance, shading, and seasonal variations to optimize overall system efficiency
- Investigate and compare the energy yield potential of two-axis and fixed-axis solar panel technologies in the specific climatic and geographical conditions of Himachal Pradesh.
- Provide recommendations on technology choices and operational practices that align with theregion's ecological and environmental goals.

3. METHODOLOGY

The feasibility study for solar panel technologies in Himachal Pradesh, specifically comparing two-axis and fixed-axis systems, employs a structured methodology utilizing PVSyst. Firstly, site selection involves identifying suitable locations based on geographical and climatic conditions, with subsequent data collection on solar irradiance and other relevant weather parameters. PVSyst is then set up with accurate geolocation data. The technology assessment phase involves inputting technical specifications for both two-axis and fixed-axis systems, utilizing manufacturers' data and industry standards to model solar panels, inverters, and associated components. The heart of the study lies in the energy yield analysis, where PVSyst simulations are run to evaluate annual energy yield, monthly variations, and other performance metrics for each technology. Financial modelling integrates cost data and calculates the levelized cost of electricity (LCOE), while sensitivity analyses assess the impact of variable parameters on feasibility. PVSyst also aids in environmental impact assessments, considering factors like land use and water consumption. The risk analysis phase evaluates potential uncertainties in input parameters. Results are interpreted, and recommendations are derived, considering economic, technical, and environmental factors. The entire process is documented comprehensively, providing a robust foundation for decision-making in adopting solar technologies in Himachal Pradesh. Figure **1** shows the methodology adopted to achieve the required objective. The software simulation of PVsyst made it possible to precisely estimate and evaluate performance while taking a number of factors into account.

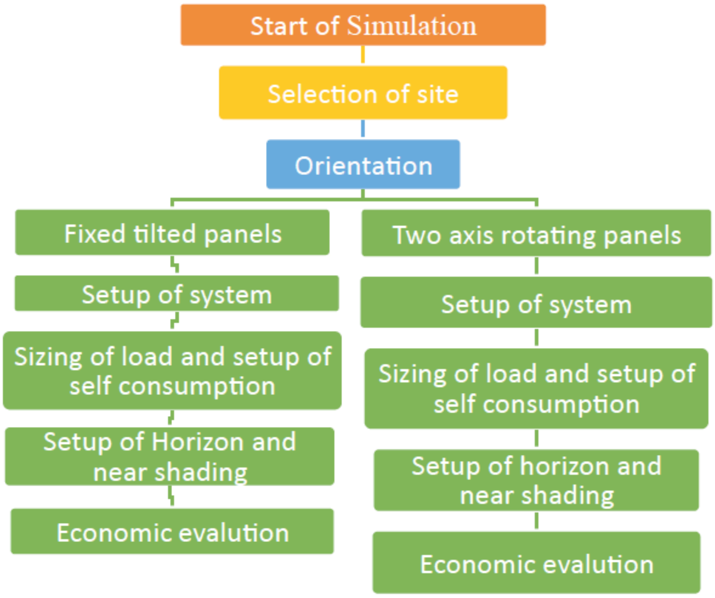

Figure 1: Methodology flow chart.

Table **1** outlines the configuration and simulation parameters for a PV system study conducted in Chagwan, Himachal Pradesh using PVsyst software. It compares a fixed tilted system with a two-axis rotating system, both connected to a 5 kW Sungrow inverter using a single MPPT. Key design aspects include optimized orientation angles (20° tilt, 57° azimuth), shading analysis via 3D modeling and horizon profiling, and adherence to electrical safety limits and grid compatibility. The system is designed to meet a residential load limited to 5 kW per local utility guidelines.

3.1. Mathematical Equations – Key Formulas Used

To evaluate the technical and economic performance of the rooftop solar PV systems, several standard photovoltaic (PV) system equations are used. These formulas help in estimating the expected annual energy output, the efficiency of system performance, and the financial viability of the installation through the payback period. The simulation results obtained from PVsyst are analyzed using these mathematical models to support comparison between fixed tilt and two-axis tracking systems. The key equations used in the analysis are described below [15]:

The equation 1 estimates the total electrical energy generated by the solar PV system in a year. It factors in the physical area of the panels, their efficiency, the amount of sunlight available annually, and losses in the system represented by the Performance Ratio (PR).

$$E = A \times \eta \times G \times PR \tag{1}$$

Where:

- E: Annual energy output (kWh/year)

Table 1: Configuration and Simulation Parameters for a PV System

Step	Description
Software Used	PVsyst Simulation Software
Study Location	Chagwan, Himachal Pradesh (Latitude: 31.6152°N, Longitude: 76.9217°E, Altitude: 769 m)
System Configurations	- Fixed Tilted System: 14 × 370 Wp modules (Vikram Solar), 5 kW Sungrow inverter - Two-Axis Rotating System: 16 × 345 Wp modules, same inverter
MPPT Details	Both systems use a single MPPT (Maximum Power Point Tracker) inverter
Orientation Settings	- Tilt Angle: 20° - Azimuth Angle: 57° - Optimized for annual irradiance using PVsyst
Shading and Horizon Analysis	- 3D near shading analysis using PVsyst - Horizon profile analysis to determine far-object shading losses
Electrical Design Constraints	- Voltage and current parameters within inverter safe operating range - Design ensures compatibility with grid-connected operation
Load Profile Consideration	Residential load capped at 5 kW based on HPSEBL rooftop solar installation guidelines

- A: Total area of solar panels (in square meters, m²)
- η: Efficiency of the solar panels (decimal)
- G: Annual solar irradiance at the location (kWh/m²/year)
- PR: Performance Ratio (decimal)

Equation 2 shows formula calculates the number of years it will take to recover the initial investment in the solar system through energy cost savings. A shorter payback period indicates a more economically viable system.

$$Payback\ Period = \frac{Total\ System\ Cost}{Annual\ Energy\ Savings} \tag{2}$$

The Performance Ratio is a measure of the quality and efficiency of the entire PV system as calculated using equation 3. It compares the actual energy produced to the theoretical maximum possible. It accounts for real-world losses such as shading, inverter inefficiencies, temperature effects, wiring losses, and maintenance downtime.

$$PR = \frac{Actaul\ Energy\ Output}{A \times \eta \times G} \tag{3}$$

3.2. Site Selection

The site selected for this case study is based on the subsidies provided for rooftop solar plants in the domestic sector by the Himachal Pradesh Government and the Central Government of India. The location chosen is Chagwan, Himachal Pradesh (Latitude: 31.6152°N, Longitude: 76.9217°E, Altitude: 769 m), as shown in Figure **2**. This comparative study of two-axis rotating and fixed-tilt solar panels follows the methodology and simulation procedures outlined in this section. The findings and discussions presented here aim to enhance the understanding of the performance and viability of these technologies in Himachal Pradesh. The PVsyst software is used for simulating the rooftop solar plant in accordance with the guidelines of the Himachal Pradesh Government and HPSEB for two different panel orientations: fixed tilt and two-axis tracking.

3.3. Orientation

In the orientation phase, field parameters such as the azimuth angle and tilt angle were set. Quick optimization was performed based on yearly irradiance yield. Additionally, the annual meteorological yield was evaluated using parameters such as the transposition factor, losses with respect to the optimum, and global irradiance on the collector plane. The azimuth and tilt angles were calculated based on the geographic location. Meteorological data was imported from the PVGIS database. Orientation simulations were conducted for both fixed tilted panels and two-axis rotating panels[16].

Fixed Tilted Panels- For the fixed tilted panels, a tilt angle of 20.0° was selected, as increasing the tilt angle to 20° in North India typically results in higher power generation. An azimuth angle of 57° was chosen to optimize yearly irradiance yield, as shown in Figure **3**.

Tracking two axis- For the two-axis panels, a tilt angle of 20.0° was used, as increasing the tilt angle to 20° in North India generally enhances power generation. An azimuth angle of 57° was set to optimize the yearly irradiance yield, as shown in Figure **4**.

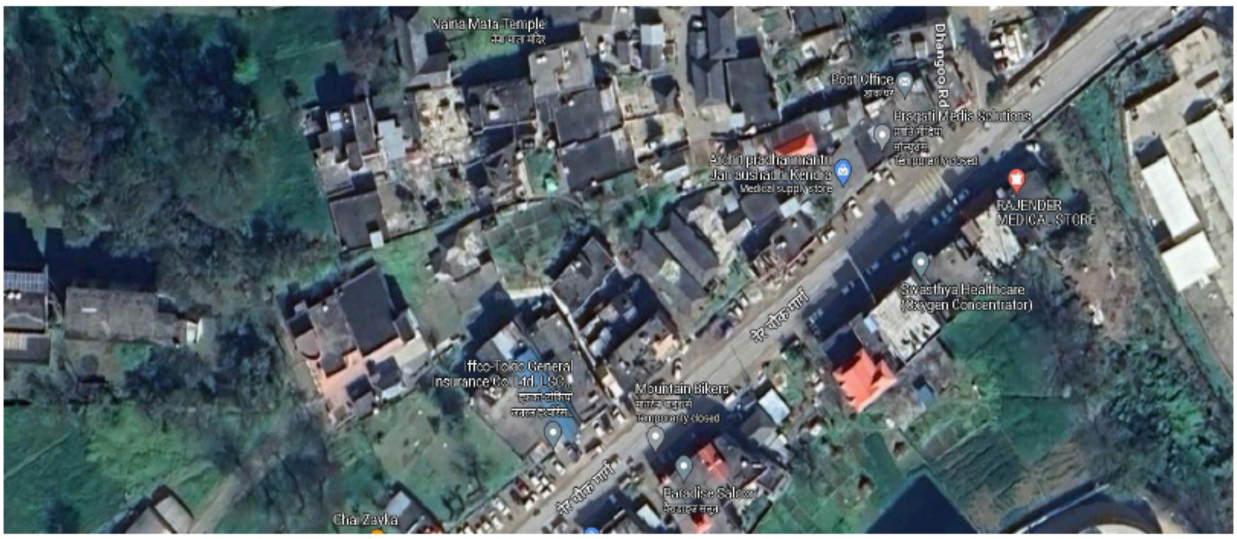

Figure 2: Satellite Image of Selected Site.

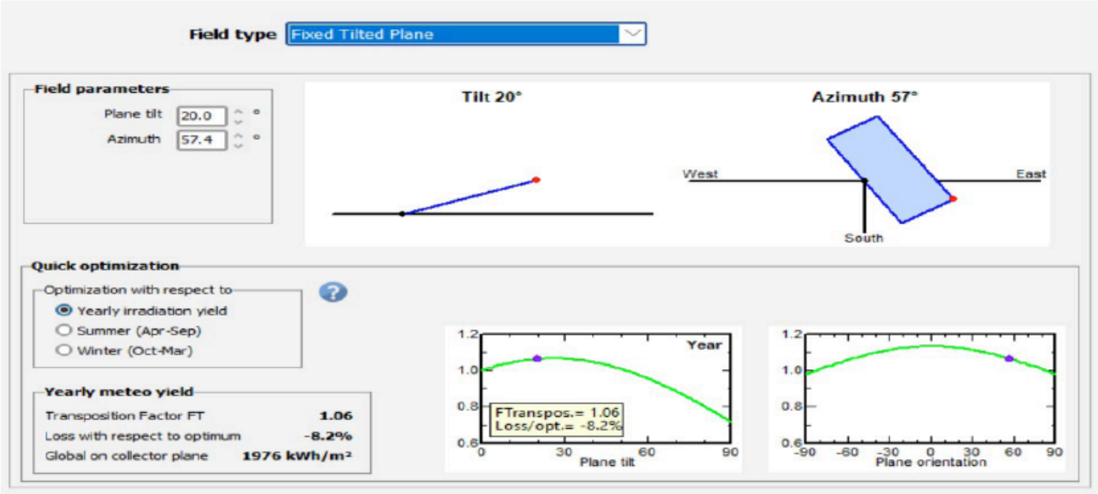

Figure 3: Fixed tilted panels orientation.

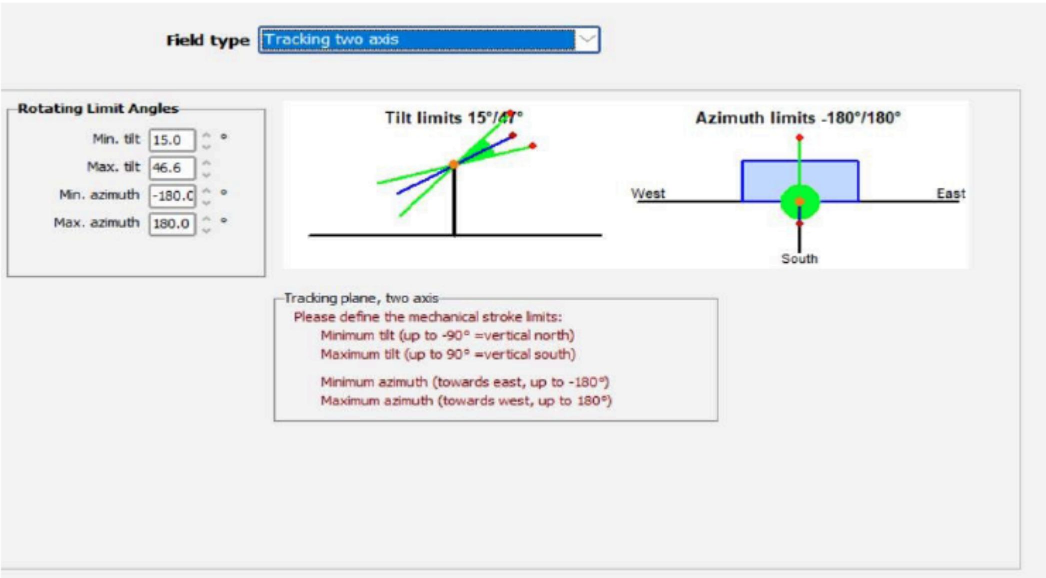

Figure 4: Tracking two axis panels orientation.

3.4. Designing and Simulation

In this step, the PV modules and inverters were selected based on system requirements. After finalizing the components, the PV array was designed. The output of this step includes the number of modules required, the area needed for module installation, the number of inverters, nominal PV power, and other related specifications.

a) PV System of fixed tilted panel

For the fixed tilted panel system, 370 Wp, 32V monocrystalline silicon solar panels from Vikram Solar were selected, along with a 5.0 kW, 50 Hz grid-connected inverter from Sungrow, as shown in Figure **5**. To meet the load requirements, approximately 14 modules connected in series with one string were used. A single inverter with an output voltage of 230V at 50 Hz was sufficient for the system.

b) PV System of rotating two axis panel

For the two-axis tracking panel system, 345 Wp, 32V monocrystalline silicon solar panels from Vikram Solar were selected, along with a 5.0 kW, 50 Hz grid-connected inverter from Sungrow, as shown in Figure **6**. To meet the load requirements, 16 modules were arranged in two strings with 8 modules connected in series per string. A single inverter with an output voltage of 230V at 50 Hz was used.

Table **2** presents a comparative overview of key design parameters for two photovoltaic (PV) system configurations: a fixed panel system and a two-axis rotation system. The comparison includes details such

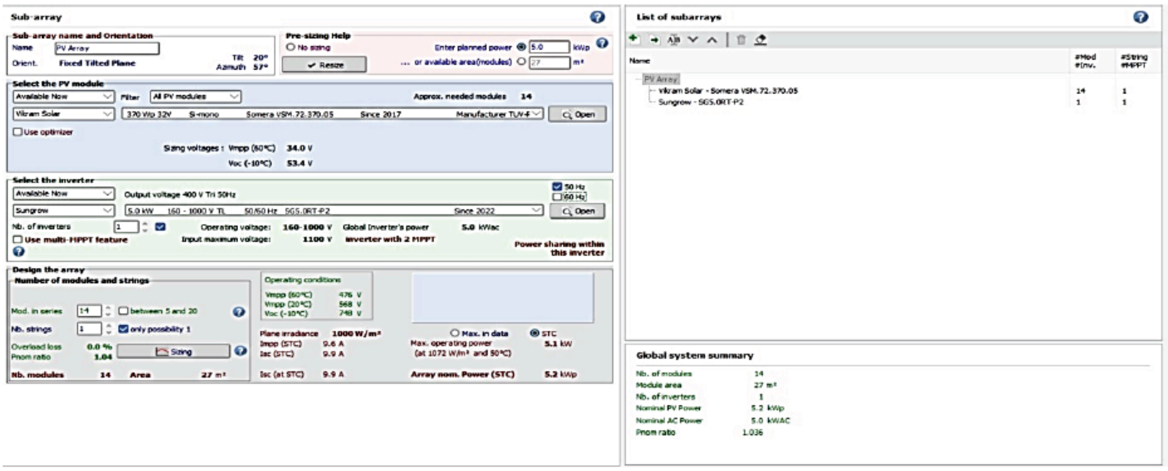

Figure 5: PV Array Design for Fixed Tilted Panel.

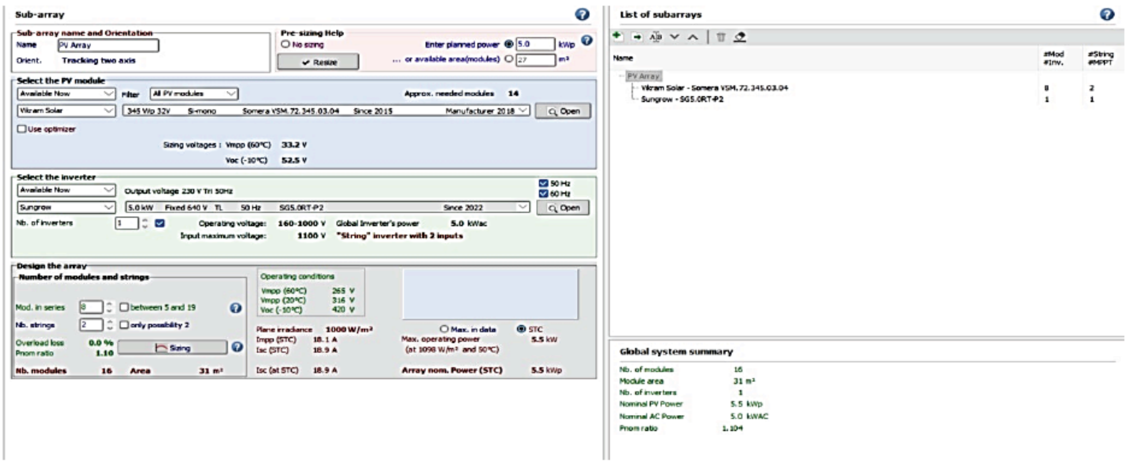

Figure 6: PV Array Design for Tracking Two Axis Panel.

as the number of modules, type of material, voltage characteristics, and power ratings.

Table 2: Design Parameters

S.No	Design Parameter	Fixed Panel	Two Axis Rotation
1	No of Modules Used	14	16
2	Material of Module	Si Poly Crystalline	Si Poly Crystalline
3	Vmpp (60°)	34.0V	33.2V
4	Voc (-10°)	53.4V	52.5V
5	No of Inverters	1	1
6	Nominal PV Power	5.2 KW	5.5 KW
7	Maximum PV Power	5.1 KW	5.5 KW
8	Nominal A.C Power	5.0 KWAC	5.0 KWAC
9	Pnom Ratio	1.036	1.104

3.5. Sizing of Load and Array Voltage

In array voltage sizing, several conditions must be considered. The array's maximum operating voltage must remain below the inverter's maximum operating voltage within the MPPT (Maximum Power Point Tracking) range, as illustrated in Figure **7**. Additionally, the array's absolute maximum voltage should not exceed the system's maximum voltage and power limits. The V-I characteristics of the PV system were also analyzed. The total electrical load, calculated through energy auditing of the selected household, was found to be 8.66 kW. However, according to HIMURJA guidelines for grid-connected rooftop solar plants [4, 17], the maximum allowable capacity is 5 kW. Therefore, a 5 kW load was considered for this case study, as detailed in Table **3**.

Table 3: Electrical Load

Electrical Load	Quantity	Wattage	Total (W)
Lamp	22	60	1320 W
Celling Fan	4	80	320 W
5Amp Socket	17	60	1020 W
15 Amps Socket	06	1000	6000 W
Total			8660 W (8.66 KW)

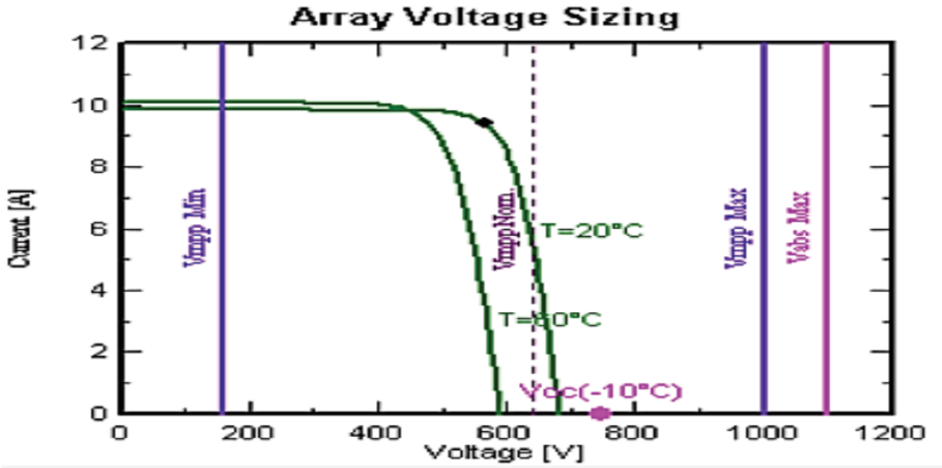

Figure 7: Array voltage sizing of fixed tilted panels.

3.5.1. Power Sizing of Fixed Tilted Panel

There are approximately 14 modules used in which the solar is Si Mono and module of Vikram solar, the sizing voltages at Vmpp (60^o) is 34.0 V and VOC (-10^o) is 53.4 V as shown in Figure **5** and Table **1**. On inverter part the output voltage is 230V, and the operating voltage of inverter is between 160V and 1000V and the maximum input voltage is 1100V. On the designing of array, there are 14 modules in series and 1 string at which the operating conditions are Impp (STC) 9.6 A and the Isc (STC) 9.9A. Therefore, the array nominal power at standard test condition is 5.2kW. Figure **8** shows the power sizing of inverter of fixed tilted panels.

3.5.2. Power Sizing of Two Axis Rotating Panel

There are approximately 16 modules of Si Monocrystalline used and module of Vikram solar, the sizing voltages at Vmpp (60^o) is 33.2 V and VOC (-10^o) is 52.5 V as shown in Figure **7** and Table **2**. On inverter part the output voltage is 230V, and the operating voltage of inverter is between 160V and 1000V and the maximum input voltage is 1100V. On the designing of array, there are 16 modules in series and 1 strings at which the operating conditions are Impp(STC) 18.1 A and the Isc(STC) 18.9A. Therefore, the array nominal power at standard test condition is 5.5kW.Figure **9** shows the array voltage sizing of two axis rotating panels and Figure **10** shows the power sizing of inverter of two axis rotating panels [18].

3.6. Setup of Horizon and Near Shading

Incidence Angle Modifier Losses refer to the reduction in energy absorption and electricity generationby solar panels due to the deviation between the sun's incident angle and the optimal perpendicular angle at which the panels are tilted. These losses are impacted by the location of the sun in the sky aswell as the direction of the solar panels as shown in Figure **11** to Figure **14** The existence of far barriers or things on the horizon that can cast shadows on solar panels,

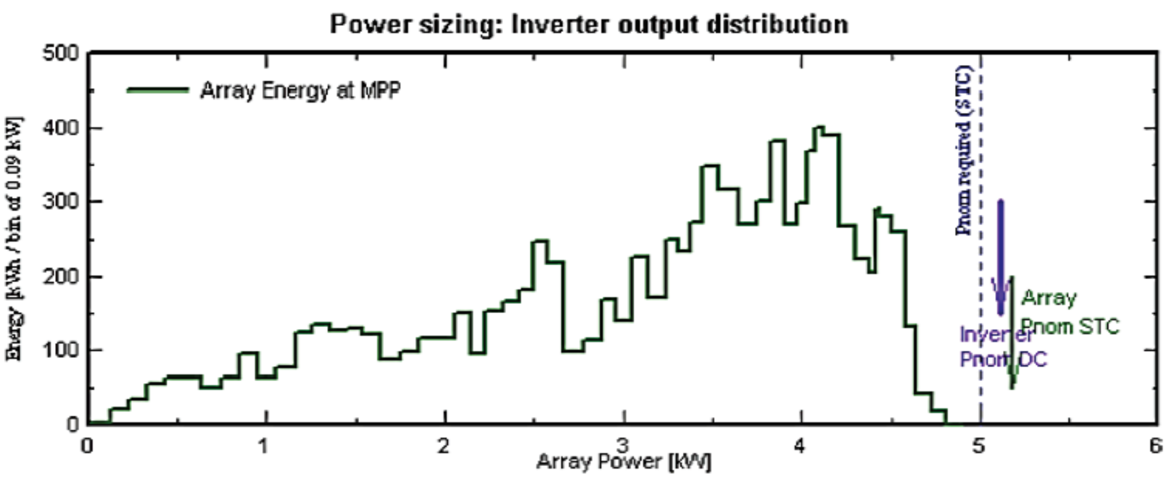

Figure 8: Power sizing of inverter of fixed tilted panels.

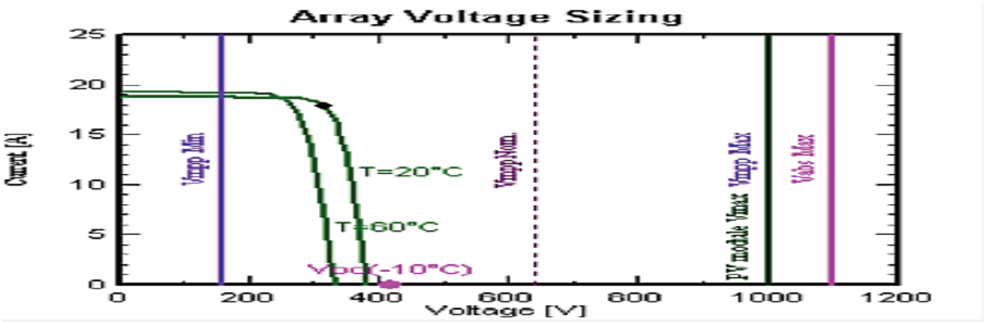

Figure 9: Array voltage sizing of two axis rotating panels.

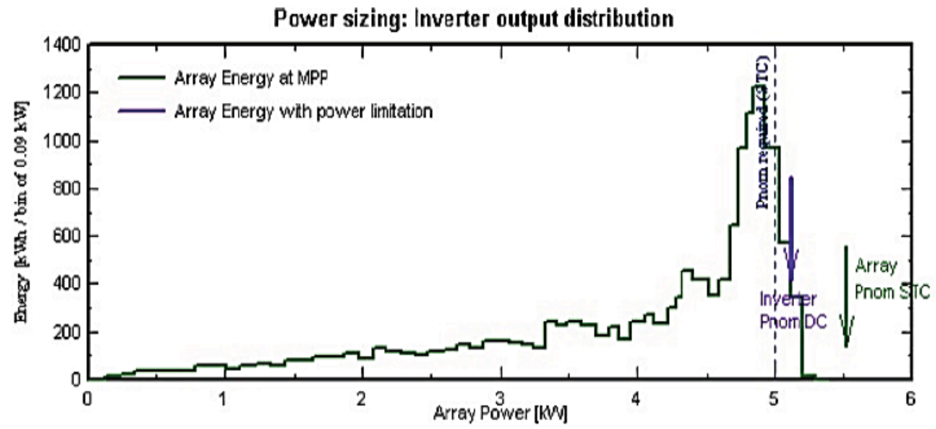

Figure 10: Power sizing of inverter of two axis rotating panels.

lowering their exposure to sunlight, is referred to as horizon line, or farshading.

4. RESULTS AND DISCUSSIONS

The data represents monthly solar energy parameters and meteorological conditions for Mandi district, Himachal Pradesh. Solar irradiance varies throughout the year, peaking in April. Diffuse horizontal irradiance and ambient temperature show seasonal trends as shown in Table **4**. The Global Incident irradiance and solar array production are highest in May and June. User consumption and solar energy contribution display monthly fluctuations, while excess energy fed into the grid is evident in the surplus energy for most months. The overall annual energy production is substantial at 8143.4 kWh, with a net grid export of 7756.9 kWh. The a negative environmental impact factor for the grid" (for clarity) indicates a lower environmental impact. This dataset provides valuable

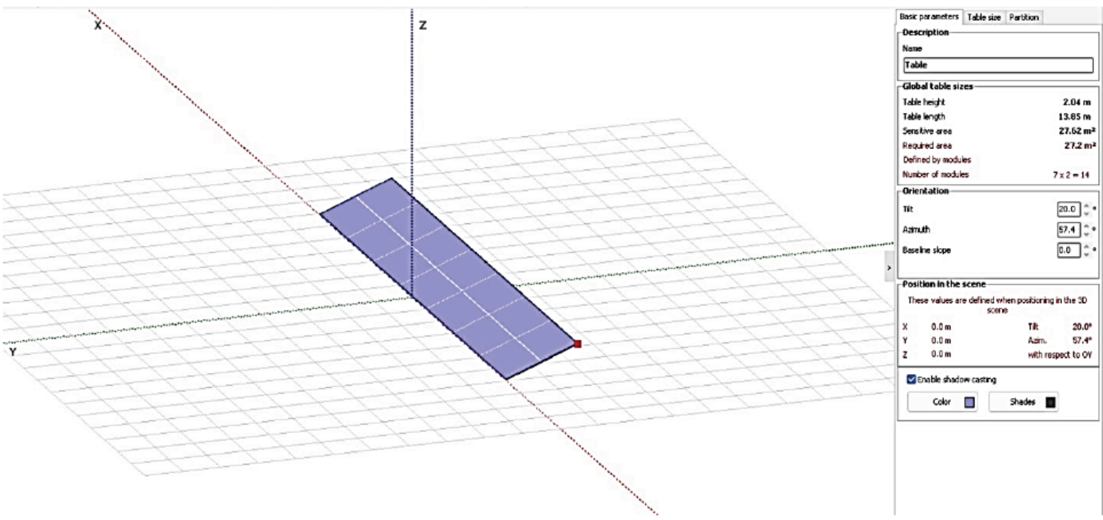

Figure 11: 3D Setup View of Fixed Tilted Panels.

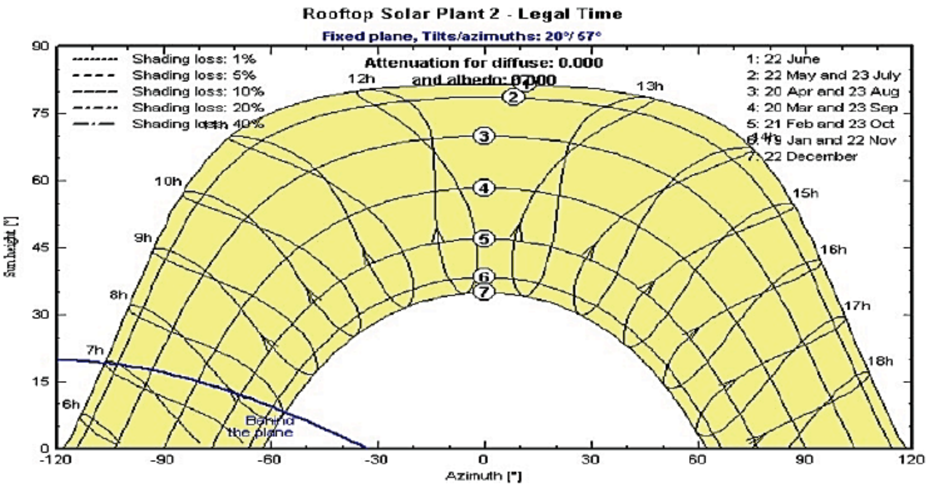

Figure 12: Path of sun over a year in case of fixed tilted panel.

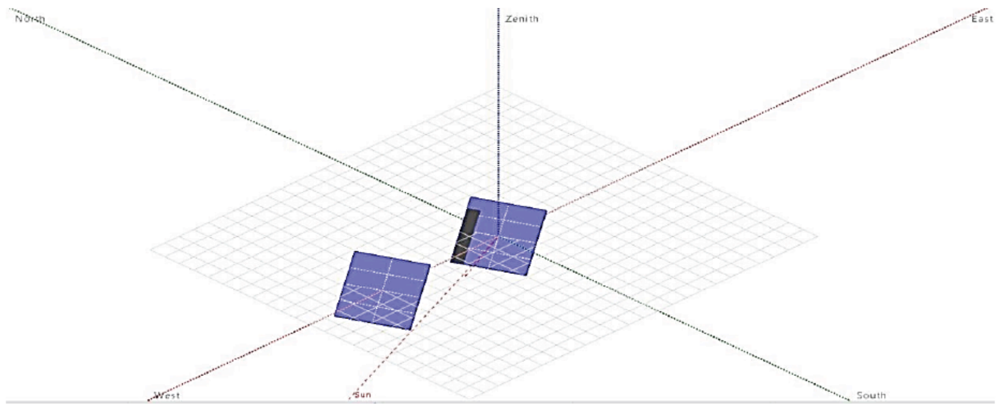

Figure 13: 3D Setup View of Two Axis Rotating Panels.

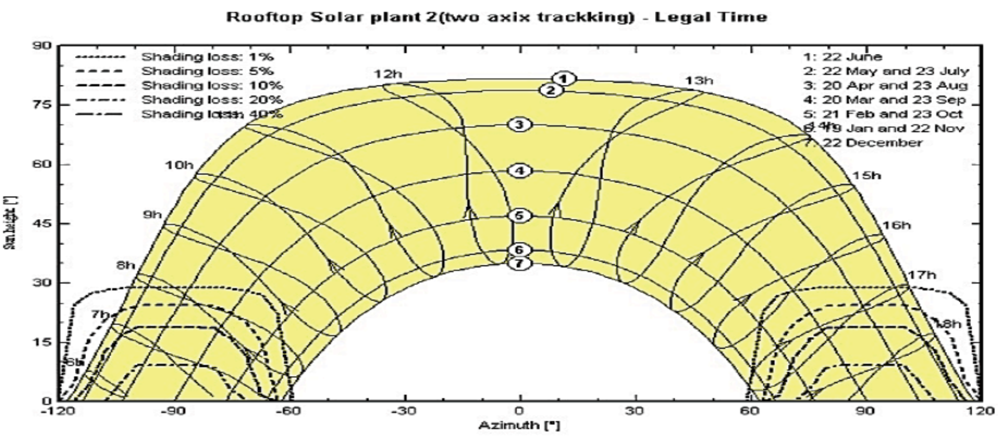

Figure 14: Path of sun over a year in case of two axis rotating panels.

insights for the feasibility study, showcasing the solar resource potential and energy dynamics for the specified location. Performance of fixed tilting and two-axis rotating solar panels in rooftop solar plants is compared in this section using the findings of a simulation research as shown in Figure **15** and **16**. The consequences for the use of solar panel technology in rooftop installations are examined, and a detailed discussion of the data and results is held. One of the most important metrics for evaluating the effectiveness of the two solar panel technologies was the photovoltaic system's efficiency. The simulation's findings, displayed in Figure **17** & **18**, demonstrate that the two-axis rotating panels produce inverter output of 6.23 kWh/day on average, whereas the fixed tilted panels achieved inverter output of 4.78 kWh/day.

Table 4: Solar Irradiation Data

Month	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
January	101.1	38.96	7.02	122.3	114.4	529.0	3720	484.9	-2.822	3235
February	128.6	37.74	8.74	148.0	139.2	627.8	3360	608.3	-2.496	2752
March	156.3	58.72	12.99	166.5	157.0	693.3	3720	670.0	-2.488	3050
April	194.8	61.29	16.84	195.3	184.7	792.5	3600	765.7	-2.139	2834
May	223.2	72.23	21.68	221.1	209.3	884.4	3720	854.8	-2.304	2865
June	207.1	78.75	23.72	198.7	187.8	792.8	3600	765.5	-2.220	2834
July	176.2	86.91	22.30	175.3	165.7	718.1	3720	692.8	-2.294	3027
August	131.1	76.74	21.38	130.9	123.4	540.5	3720	519.0	-2.253	3201
September	161.0	60.78	19.42	171.0	161.8	702.5	3600	679.0	-2.384	2921
October	154.4	46.36	16.04	172.8	162.8	712.7	3720	689.5	-2.612	3030
November	126.3	34.53	12.02	150.6	141.0	629.5	3600	523.9	-2.673	3076
December	101.0	35.32	7.57	121.7	113.3	520.3	3720	503.5	-3.038	3216
Year	1861.1	688.34	15.84	1974.2	1860.5	8143.4	43800	7756.9	-29.724	36043

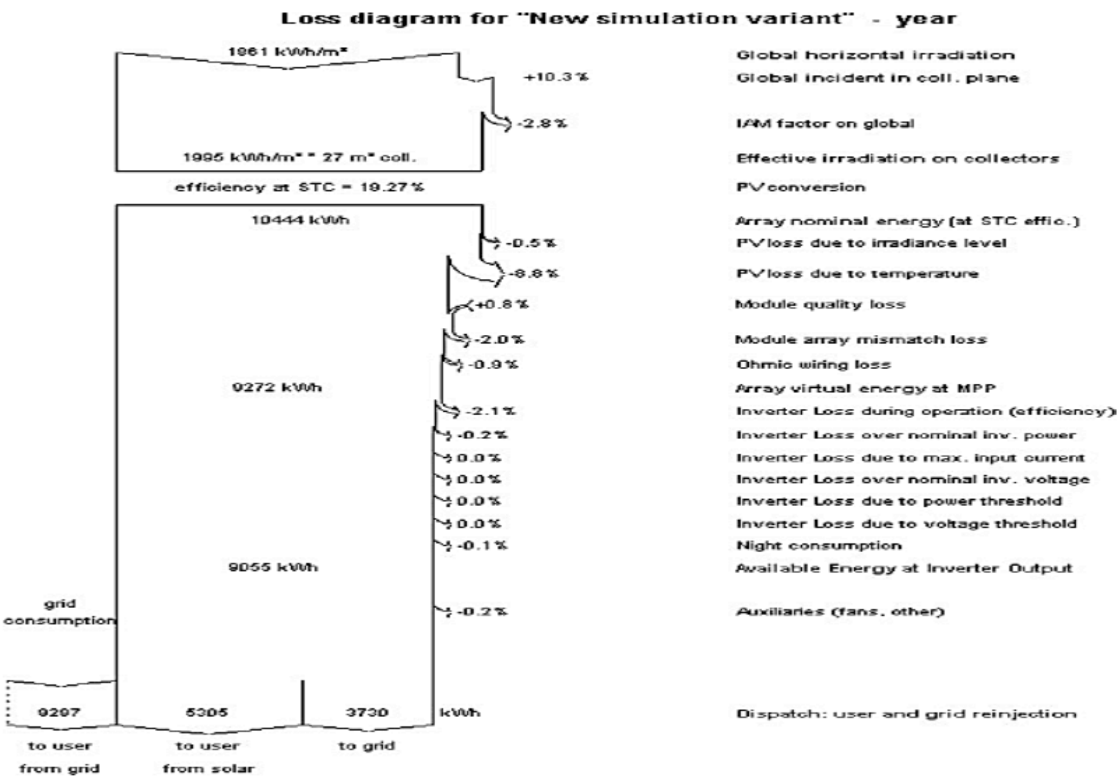

Figure 15: Loss diagram of fixed tilted panel.

Both solar panel systems were assessed for their economic viability, taking into consideration factors such as initial installation costs, maintenance costs, and prospective government incentives or subsidies. The cost-effectiveness of fixed tilting panels over two-axis rotating panels was seen, as Table **5** & **6** makes clear. Fixed panels clearly had a faster payback duration than rotating panels, with the former having a payback period of 1.8 years and the latter having a payback period of 2.3 years.

The Table **7** shows a comparative study which concludes that while two-axis tracking panels offer higher daily output, fixed tilted panels are more cost-effective and better aligned with the economic realities and subsidy frameworks of residential consumers in Himachal Pradesh. Fixed panels require less maintenance and space, making them the preferred choice for widespread adoption. Limitations include the scope of simulation assumptions and site-specific variables. Future work may expand to hybrid systems or AI-based optimization.

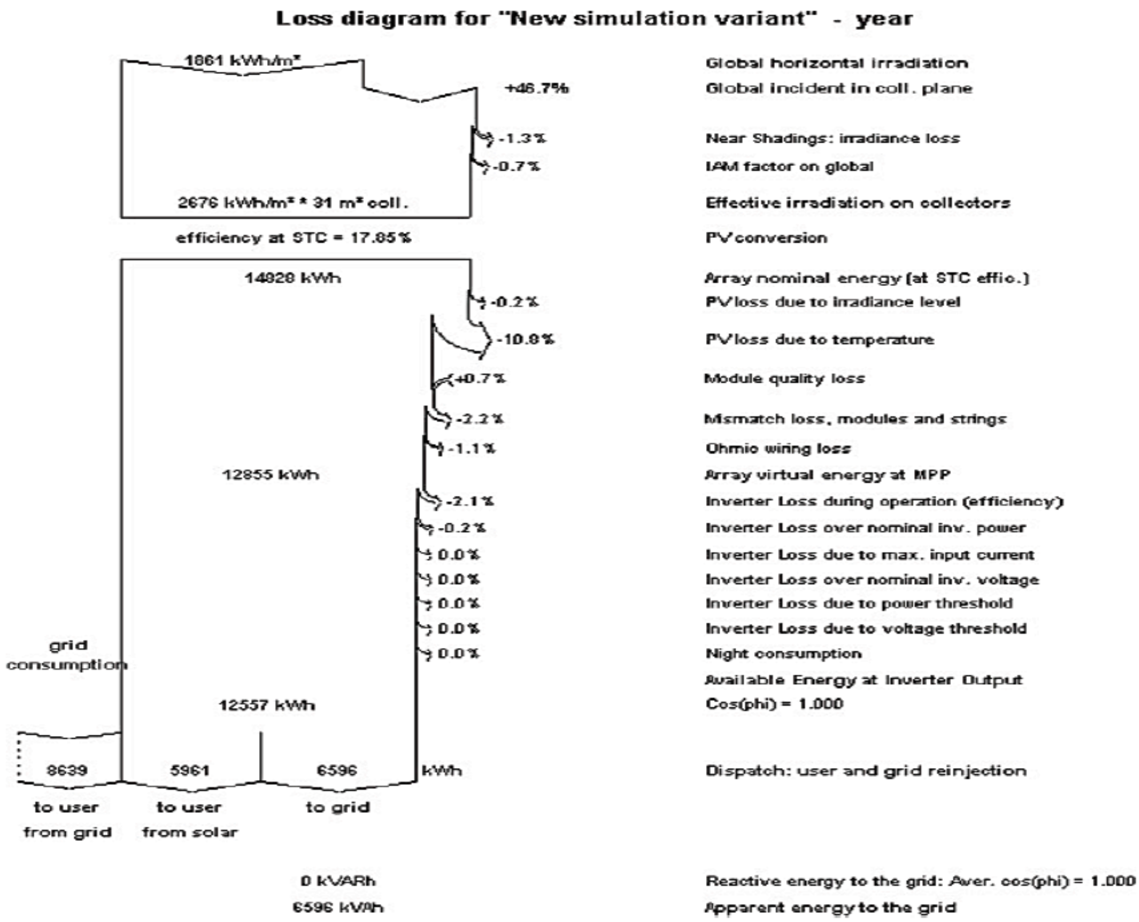

Figure 16: Loss diagram of two axis rotating panel.

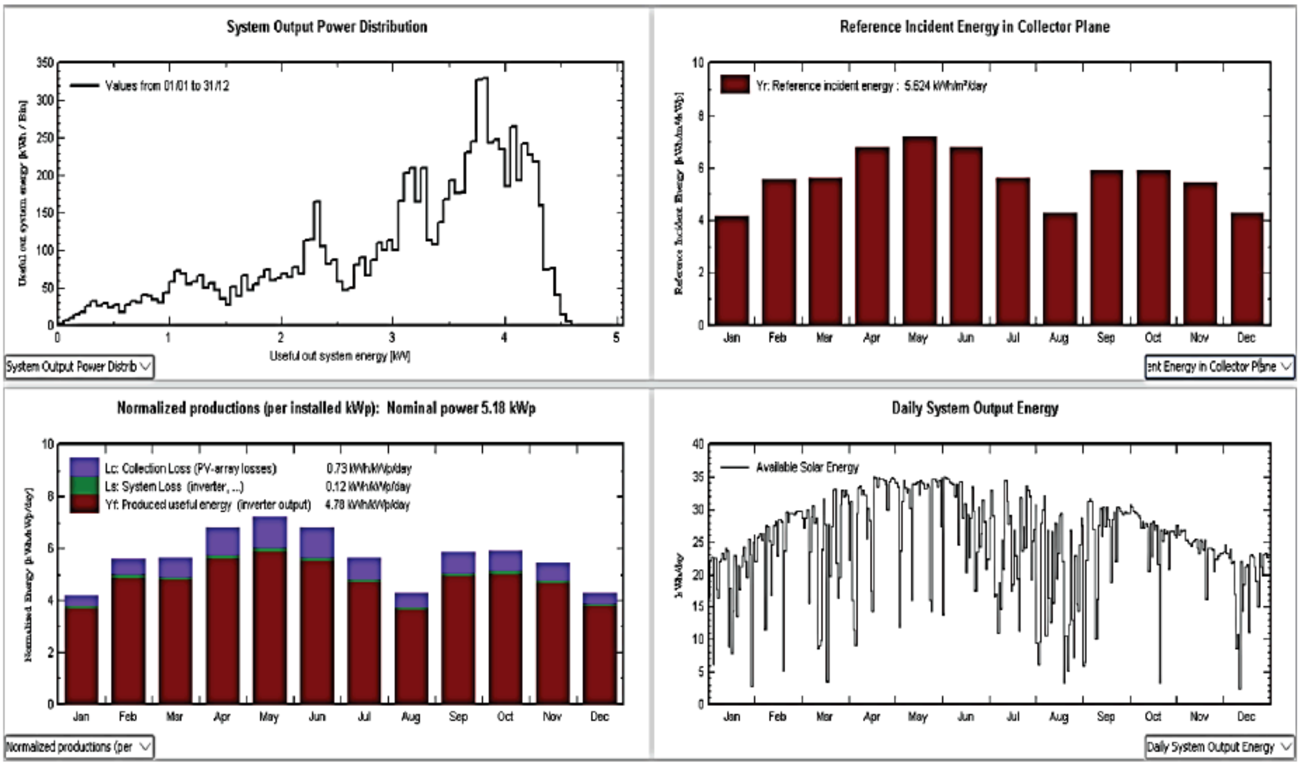

Figure 17: Output Result of fixed panel plant.

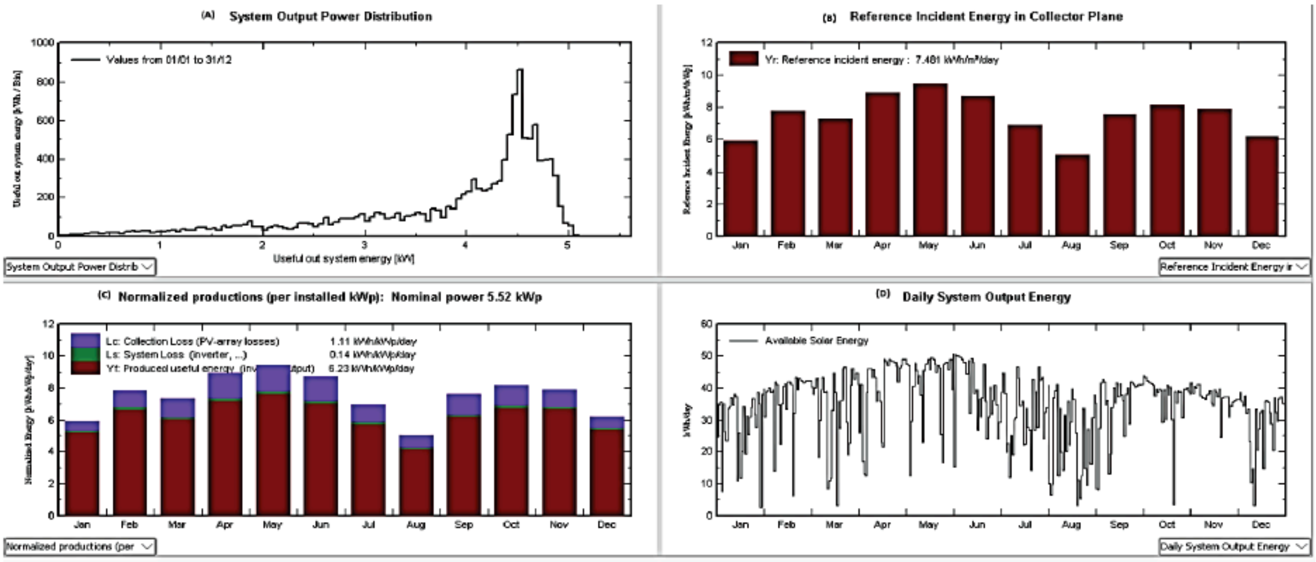

Figure 18: Output Result of two axis rotating plant.

Table 5: Financial Analysis of Fixed Mounted Panels

Year	Electricity Sale	Own Funds	Run Cost	Deprec Allow	Taxable income	Taxes	Aftertax profit	Self-cons Saving	Comul Profit	% profit
0	0	64,740	0	0	0	0	0	0	-64,740	0.0%
1	15,957	0	2,750	8,816	4,391	0	13,207	22,654	-27,879	55.4%
2	16,116	0	2,929	8,816	4,371	0	13,187	22,881	7,189	111.1%
3	16,277	0	3,119	8,816	4,342	0	13,158	23,110	43,457	167.1%
4	16,440	0	3,322	8,816	4,302	0	13,118	23,341	79,916	223.4%
5	16,604	0	3,538	8,816	4,251	0	13,067	23,574	1,16,557	280.0%
6	16,770	0	3,768	8,816	4,187	0	13,003	23,810	1,53,370	336.9%
7	16,938	0	4,013	8,816	4,110	0	12,926	24,048	1,90,343	394.0%
8	17,108	0	4,273	8,816	4,018	0	12,834	24,289	2,27,466	451.4%
9	17,279	0	4,551	8,816	3,912	0	12,727	24,531	2,64,725	508.9%
10	17,451	0	4,847	8,816	3,788	0	12,604	24,777	3,02,106	566.6%
11	17,626	0	5,162	8,816	3,648	0	12,464	25,025	3,39,595	624.6%
12	17,802	0	5,498	8,816	3,489	0	12,305	25,275	3,77,174	682.6%
13	17,980	0	5,855	8,816	3,309	0	12,125	25,528	4,14,827	740.8%
14	18,160	0	6,236	8,816	3,109	0	11,924	25,783	4,52,534	799.0%
15	18,342	0	6,641	8,816	2,885	0	11,701	26,041	4,90,275	857.3%
16	18,525	0	7,073	8,816	2,637	0	11,452	26,301	5,28,029	915.6%
17	18,710	0	7,532	8,816	2,362	0	11,178	26,564	5,65,771	973.9%
18	18,897	0	8,022	8,816	2,060	0	10,876	26,830	6,03,476	1032.2%
19	19,086	0	8,543	8,816	1,727	0	10,543	27,098	6,41,117	1090.3%
20	19,277	0	9,099	8,816	1,363	0	10,179	27,369	6,78,665	1148.3%
21	19,470	0	9,690	8,816	964	0	9,780	27,643	7,16,087	1206.1%
22	19,665	0	10,320	8,816	529	0	9,345	27,919	7,53,351	1263.7%
Total	3,90,482	84,740	1,26,779	1,93,950	69,752	0	2,63,702	5,54,389	7,53,351	1263.7%

Table 6: Financial Analysis of Two Axis Rotating Panels

Year	Electricity Sale	Own Funds	Run Cost	Deprec Allow	Taxable income	Taxes	After tax profit	Self-cons Saving	Comul Profit	% profit
0	0	117,400	0	0	0	0	0	0	-1,17,400	0.0
1	28,185	0	2,500	19,955	5,731	0	25,685	25,458	-66,256	43.6%
2	28,185	0	2,650	19,955	5,581	0	25,535	25,458	-15,263	87.0%
3	28,185	0	2,809	19,955	5,422	0	25,376	25,458	35,572	130.3%
4	28,185	0	2,978	19,955	5,253	0	25,208	25,458	86,238	173.5%
5	28,185	0	3,156	19,955	5,074	0	25,029	25,458	1,36,725	216.5%
6	28,185	0	3,346	19,955	4,885	0	24,840	25,458	1,87,023	259.3%
7	28,185	0	3,546	19,955	4,684	0	24,639	25,458	2,37,120	302.0%
8	28,185	0	3,759	19,955	4,472	0	24,426	25,458	2,87,005	344.5%
9	28,185	0	3,985	19,955	4,246	0	24,201	25,458	3,36,664	386.8%
10	28,185	0	4,224	19,955	4,007	0	23,962	25,458	3,86,083	428.9%
11	28,185	0	4,477	19,955	3,754	0	23,708	25,458	4,35,250	470.7%
12	28,185	0	4,746	19,955	3,485	0	23,439	25,458	4,84,148	512.4%
13	28,185	0	5,030	19,955	3,200	0	23,155	25,458	5,32,761	553.8%
14	28,185	0	5,332	19,955	2,898	0	22,853	25,458	5,81,072	595.0%
15	28,185	0	5,652	19,955	2,578	0	22,533	25,458	6,29,063	635.8%
16	28,185	0	5,991	19,955	2,239	0	22,194	25,458	6,76,715	676.4%
17	28,185	0	6,351	19,955	1,880	0	21,834	25,458	7,24,008	716.7%
18	28,185	0	6,732	19,955	1,499	0	21,453	25,458	7,70,920	756.7%
19	28,185	0	7,136	19,955	1,095	0	21,049	25,458	8,17,427	796.3%
20	28,185	0	7,564	19,955	667	0	20,621	25,458	8,63,507	835.5%
21	28,185	0	8,018	19,955	213	0	20,167	25,458	9,09,133	874.4%
22	28,185	0	8,499	19,955	0	0	19,686	25,458	9,54,277	912.8%
Total	6,20,075	117,400	108481	4,39,000	72,862	0	5,11,594	5,60,083	9,54,277	912.8%

Table 7: Comparative Analysis

Parameter	Fixed Panels	Two-Axis Panels
Modules Used	14	16
System Capacity (kW)	5.2	5.5
Avg. Daily Output (kWh)	4.78	6.23
Payback Period (Years)	1.8	2.3
Installation Cost (□)	64,740	1,17,400
ROI (%) over 22 Years	1263.70%	912.80%

4. CONCLUSION

This comparative study evaluates the performance and viability of fixed tilted and two-axis rotating solar panels within the unique climatic and geographical context of Himachal Pradesh. Using PVsyst software simulations, the results indicate that although two-axis rotating panels generate slightly more daily energy (6.23 kWh/day vs. 4.78 kWh/day), fixed tilted panels offer superior economic performance. With a shorter payback period of 1.8 years, lower installation and maintenance costs, and a higher return on investment, fixed systems are more financially advantageous for residential rooftop applications.

Environmental impact assessments further support the adoption of fixed tilted panels. Their simpler design and reduced mechanical complexity make them more sustainable, both from both environmental and operational perspectives, aligning well with Himachal Pradesh’s goals for ecological preservation. Additionally, fixed panels are more practical for large-scale implementation under the state’s Grid-Connected Rooftop Solar Scheme, due to ease of installation and maintenance.Based on the findings, fixed tilted solar panel systems are recommended as the optimal solution for residential rooftop installations in Himachal Pradesh. This recommendation is grounded in their balanced performance, cost-effectiveness, and alignment with regional and national sustainability objectives. Future research could explore hybrid systems and storage integration to further enhance system reliability and energy independence, especially in remote or grid-limited areas.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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