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Performance Degradation Analysis of 100 W Solar Pv Module: an Experimental Study

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Abstract – Photovoltaic (PV) systems are increasingly being deployed for distributed and utility-scale power generation. However, accurate estimation of long-term performance degradation and economic return remains essential for system planning. This study examines the longitudinal performance of an experimental 100 W poly-crystalline solar PV module using annual average daily measurement to analyse the payback economics and end of life forecasting. The measurement performed is for current, voltage, power, irradiance, and temperature under fixed load condition. The results show that the cumulative energy degradation is 4.57% over period from 2022 to 2025 and the average annual decline is 1.52%. The payback period for small scale PV system is around 5 years. When a small system scales to a large scale PV system, the payback period improves and overall improvement in efficiency and performance analysis. The performance behavior of the module and the energy-generating features are assessed using the gathered field data. The end-of-life (EOL) performance of the PV module is estimated using a lifetime model based on degradation. Afterward, the payback economics of the PV system is calculated based on the installation cost, energy production, and the electricity tariff. In the later stage, the results are generalized for a 1 MW solar PV-plant to analyse the large-scale feasibility.

Keywords: Degradation effect, End of life Estimation, Energy Generation, Payback period, Performance assessment, Real time systems, Sustainability, Utility-scale systems.

1. Introduction:

Electricity is the most important part of our life in today's world. Mainly, sources of electricity are fossil fuels, releasing the large quantities of greenhouse gases which causes global warming and unstable the climate [1] . During the current situation of the depletion of coal and overexploitation across the worldwide, the energy demand is going to be increased by the non-conventional energy sources like solar energy, wind energy, biomass energy, geothermal energy and tidal energy etc. Around the world, people are making a transition from non-renewable energy sources to renewable energy sources like Solar Power. The best way to the utilization of the solar power is by using solar panels or PV technology [2], [3]. Solar energy is the power that comes from the sun which gets converted into thermal or electrical energy. Solar energy technologies capture the energy from the sunlight to the generation of electricity. PV technology and Concentrated solar power are two main technologies of solar energy, but in today's world PV technology is the best method for generating electric power by using solar cells to convert the energy from the sunlight into electricity. Solar cell is the basic unit of PV system which is made up of semiconductor materials like polycrystalline silicon and monocrystalline silicon materials. India is growing into an economically viable sector for PV installations, with the total 70 GW installed solar PV capacity likely to increase to 145.9 GW by 2030 [4]. One of the most easily available the alternative source of energy is Solar power which is growing rapidly and gathering an increasing amount of interest. It has been found recently by researchers that the Earth's fuel reserves are being depleted by decades of use of traditional energy sources. Due to this, the output of conventional energy has increased and fuel consumption has increased [5]. Research indicates that while traditional energy fuels are becoming less abundant on Earth, demand for them is rising. On the other hand, unlike conventional fuels, which are predicted to run out on Earth's surface, non-conventional energy sources are naturally occurring and renewable. This is a result of non-conventional fuels' innate lifespan on the surface of the Earth. Are you aware of solar photovoltaic cells, a renewable energy source that requires very little maintenance and has no operating costs? Nevertheless, the installation comes at a hefty initial expense [6]. This energy source is pollution-free, silent, and kind to the environment. Since photovoltaic energy is a renewable energy source, its demand is rising globally, while the need for traditional fuels is steadily declining [7]. The planet's long-term energy needs cannot be met by conventional fuels, and there is a limited supply of storage space for them.

In today's era, solar PV installations have expanded quickly with the lower cost of modules, favorable energy policies and increased efficiencies around the world. For this reason, there is increased interest in renewable energy sources like photovoltaic cells. Worldwide demand for solar energy has been rising as a result of various nations' subsidies [8]. The need for solar PV energy sources has increased as a result of this. Since energy unit prices are not included in their power consumption bills, consumers are ready to pay the one-time capital installation cost associated with purchasing solar PV energy [9].

PV modules have lifespan of approximately 25 years. But due to some parameters affect their performance and reliability over time. Due to its outdoor location, PV installations is exposed to environmental variables such as cloud cover, temperature, solar irradiation and humidity which have a considerable long term effect on its performance [10]. Return on investment also affected due to the low term performance of solar PV panels. PV systems provide practical and sustainable solution for clean energy generation in India, where level of solar irradiation is high and energy demand is growing quickly. Even with the quick growth of PV installations, the long term financial sustainability of solar systems continues a significant issue for investors, government officials and stakeholders also. Although the PV system's initial capital cost has significantly fallen, the system's collective financial performance depends not only on the cost of installation but it also depends on variable factors such as declined system, operational efficiency, energy yield and electricity costs over system's lifespan. Among these, PV module performance deterioration plays a major factor for assessing the generation of energy and financial benefits. PV module degradation factors mainly dependent on environmental parameters as well as operation and maintenance. Even while this decrease might insignificant on an annual basis, over the duration of the system's lifespan it can have a substantial impact on total energy generation and as a result, financial parameters like Levelized cost of Energy (LCOE), the time of payback and Net Present Value (NPV). Some standards established by International Electro-Technical Commission (IEC), i.e. IEC 61646 for thin film modules, IEC 61215 for wafer based crystalline modules and IEC 61730 have contributed to make sure PV modules long-term reliability to certain limit [11], [12], [13]. Ideally, these standards are designed to replicate the range of stresses that PV modules are likely to encounter under real operating conditions over a service life of approximately 20-25 years [14]. However, compliance with IEC standards does not ensure long-term performance or guarantee that service life of PV modules.

Many studies treat system lifespan as constant value i.e. 25 years without particularly connecting it to standards of performance based on degradation. But practically, a PV system is said to have accomplished its EOL, when its output declined below a particular limit, typically around 80% of its original rated output. Consequently, accurate lifespan assessment requires degradation behavior in both performance analysis and financial simulations.

Small scale PV system like 100W module offer a reliable framework for thorough study in this situation. These small systems are basically used in experimental investigation, residential applications etc. Such systems provide a suitable platform for studying degradation behavior, performance trends, and financial sustainability with insights that can be extended to larger–scale installations. The objective of this research is to construct a complete structure for assessing a 100W solar PV system's payback duration and EOL by incorporating financial evaluation with degradation modelling.

This paper analyses field-measured data from a 100 W rooftop PV module to estimate degradation behavior, EOL performance, and economic payback, and further extrapolates the analysis to a 1 MW solar PV plant.

Analysing a system's present performance and quantifying the end-of-life and payback period, are crucial before making a large investment in solar PV plants at a specific location and is challenging too. Thus, the objective of this paper is as follows:

a. To assess the performance of a 100 W test system using real-time measured data.
b. Quantifying the EOL and Payback period of the plant
c. Scaling the plant characteristics from 100 W to utility scale for large-scale plant deployment
d. Optimization to improve performance

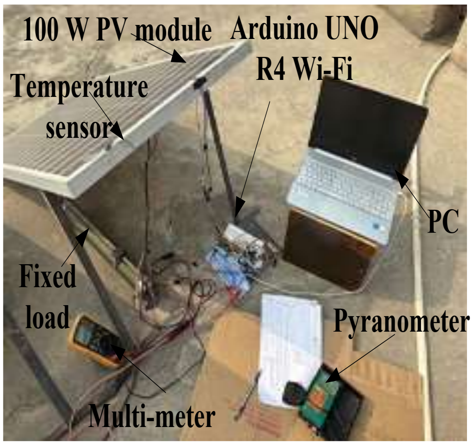
This paper involves the novelty in terms of mixed technical analysis interlinking with the plant economics and EOL. Also, the extrapolation of the characteristics of a 100 W solar plant into 2 MW paves to take correct decision before and get idea of large plant before actual deployment. At the end optimizing the system for batter performance. Thus, technical performance, life-assessment, payback, feasibility and scalability are the novelty of this paper.

This paper's outline is as follows: The experimental setup and modelling of PV system are explained in Section II. Section III analyses the methodology. Section IV contains the experiment's results and discussions. The experimental data and conclusions are presented in Section V.

2. Experimental Setup and Modelling of Solar PV system

2.1. System Description and Site Specification

In this study, a 100W solar PV panel based experimental setup was installed on the roof of academic block-II at GLA University, Mathura U.P. India in 2022, with a geographical coordinate for our site are 27°29'33" N latitude and 77°40'25" E longitude and fixed tilt angle of 28° facing south with on load. The pictorial view of the entire setup is shown in Fig. 1 (a). The various components of the setup are pyrometer used for measuring solar irradiance, temperature sensors used to measure module surface temperature, multi-meter, rheostat load at fixed ohmic value and the Arduino UNO R4 Wi-Fi system for recording measured data. The entire data are collected through micro-controller and transmitted to Google Cloud Sheet, where entire data are automatically stored for further analysis process. The detailed specification of different parts of experimental setup and Wi-Fi module for data recording is given in Table I and Table II, respectively. The tables display the values that were used in their standard measures.



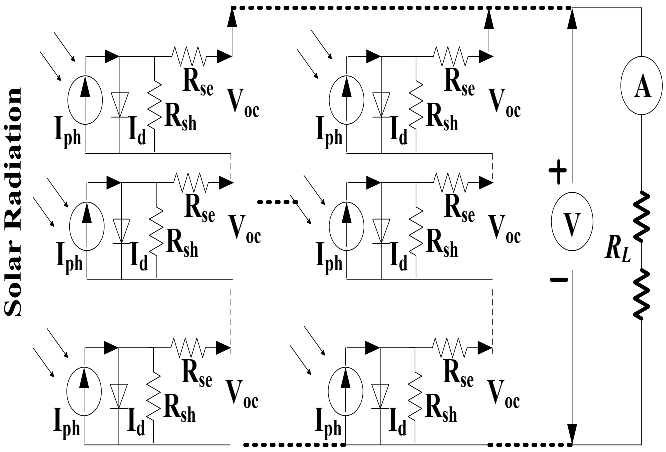


Fig.1 Experimental setup for real time operating system

Fig. 2 Equivalent circuit for PV module

Table:1 Specifications of 100W PV Module

Electrical Parameters	Rating /Type	Physical Parameters	Specifications	Physical Parameters	Specifications
Maximum power	100 W	Length*Width*Thickness	1150*675*35	Frame Material	Anodized Aluminium Alloy
Short Circuit Current (I_{sc})	6.07 A	Weight	10.15 kg	Mounting Holes Pitch (Y/X)	575mm/633mm
Open Circuit Voltage (Voc)	21.97V	Solar cells per Module	36	Connector	IP67 rated/ MC4 compatible
Voltage at Max. Power (Vmp)	17.46V	Arrangement	9*4	Cable cross section	4mm^2
Current at Max. Power (Imp)	5.73A	Solar Cell Type	Polycrystalline Silicon		
Max. System Voltage	1000V	Encapsulate	Ethylene Vinyl Acetate		
Module Efficiency	12.88 %	Front Cover	Tempered and Low Iron	Glass/3.2mm/4mm	

Table: 2 Specifications of Sensors

Name	Specifications
Arduino UNO R4 Wi-Fi	DC current per Input/output Pin: 8mA DC current for 3.3V Pin: 50mA, Flash Memory: 256 KB, Clock speed: 48MHz, I/P voltage: 6-24 V, Operating Voltage: 5V,

ACS712 30A	Output rise time: 5µs in response to step I/P current BW: 80kHz O/P error: 1.5% at T_A = 25°C output sensitivity: 66-185mV/A
Pyranometer	Range: 2000W/m^2 Accuracy: ±10W/m^2 temp. error: ±0.38 W/m^2/°C from 25°C Sampling time: 0.025s
MAX6675 K-type thermocouple	Current consumption: 700µA, 1.5mA (max) temperature range: 0-1024°C (MAX6675), 0-80°C (probe) conversion time: ~170ms
Voltage V<<25	Voltage Sensor Module, I/P range: DC (0-25V), Pins: 5/3.3 V

2.2. Modelling of Experimental setup using PV module Equivalent circuit

The simplest and most popular model for PV cells is the one-diode type as shown in Fig. 2. The entire solar panel is modelled using a series and parallel combination of individual PV cells. A single cell consists of current source (I_{ph}) known as photo-current in parallel with diode, a series (R_{se}) and parallel resistance (R_{sh}) with single cell convert an ideal equivalent model into practical. The photocurrent I_{ph} is linearly related to solar radiation G_{irr}., ambient temperature, output voltage and current. The characteristics of a single cell and hence the entire module can be modelled as (1), (2), (3), (4) and (5) [15], [16]:

$$I = n_{sh}\left[I_{Ph} - I_o\left[e^{q\frac{(V+n_sIR_s)}{nkT}} - 1 \right] - \frac{V + n_sIR_s}{R_{sh}n_s} \right] \quad (1)$$

where I is the current through load, n_{sh} is the number of parallel branches of n_s series connected PV cells, $I_o\left[e^{q\frac{(V+n_sIR_s)}{nkT}} - 1 \right]$ is the diode current of each branch with n_s cell connected in series. Also, V is the voltage across load end, k is the Boltzmann constant, working temperature T in kelvin, I_o is diode saturation current. The open-circuit voltage and the short-circuit current are two important metrics used to assess a photovoltaic cell's performance. When the voltage across the cell is zero, the short circuit current is obtained. Therefore, V = 0 from (1) give nonlinear short circuit current dynamics for practical PV module (I_{sc}) as shown (2).

$$I_{sc} = n_{sh}\left[I_{Ph} - I_o\left[e^{q\frac{(n_sI_{sc}R_s)}{nkT}} - 1 \right] - \frac{n_sI_{sc}R_s}{R_{sh}n_s} \right] \quad (2)$$

By approximating and neglecting the series and shunt resistance, the short circuit current will be represented as (3).

$$I_{sc} = I = n_{sh}\left[I_{Ph} \right] \quad (3)$$

Similarly, when the module current is zero, the open circuit voltage (V_{oc}) of the module is obtained. This is achieved by replacing load current (I) as zero in in (1) and neglecting R_{se} and R_{sh} to get an approximated relationship representing the dynamics of open circuit voltage (V_{oc}) at module terminals can be represented as (4).

$$V_{oc} = \frac{nn_skT}{q}\ln\left[{}^{I_{Ph}}\!/_{I_o} + 1 \right] \quad (4)$$

Thus, the power (P) of a module or practical cell can be approximated as (5).

$$P = n_{sh}\left[I_{Ph} - I_o\left[e^{q\frac{(V+n_sIR_s)}{nkT}} - 1 \right] - \frac{V + n_sIR_s}{R_{sh}n_s} \right]V \quad (5)$$

3. Methodology

A study using real-time data has been adopted as the methodology of this system. The real-time data is collected using a small-scale experimental setup of rooftop PV system. Initially, the equivalent model and system parameters that need to be collected and analysed are identified using a literature survey. Thereafter, mathematically, the objective parameters are analysed quantitatively and graphically; the entire process involves data collection, invalid data cleaning, and result estimation, scaling up the results to utility-scale plants and comparison of the Lab-scale and utility-scale systems. Thus, the objectives of the paper concise the methodology into a) Analysis of the system, including input, measured parameters and performance, b) Quantization of end-of-life based on performance, c) Economic modelling to estimate Payback period, d) Model scaling criteria to project the results up-utility scale and comparison and e) optimization to improve performance. The parameters measured, evaluated for technical, economic and end life assessment, are given in Table 3, with its brief significance.

3.1. Technical, Economic and EOL assessment Terms

To evaluate the performance assessment and economic analysis of 100W solar PV system standard parameters are defined by IEC 61724 are examined [17]. These parameters may be assessed on daily, monthly and annual basis which includes. The collected input parameters voltage (V_{dc}), current (I_{dc}), Irradiance (G_{irr}), temperature module (T_{mod}) and ambient (T_{ab}), are recorded with a sampling frequency of 1.6 mHz. The sampling rate for recording data is 200 mHz, further the data is down sampled at a rate of 1.6 mHz and aggregated to the monthly and yearly basis for representation.

Table 3: PV module parameters and its Expressions

Parameter	Expression	Unit	Comment
Power output [18]	$P_{out} = V_{dc} \times I_{dc}$	W	Output power in Watt with constant load scenario
Energy Generated	$E_g = \sum_{i=1}^{n} P_{dci} \times \Delta t$	kWh	Energy output estimated on daily, monthly or yearly basis using a sampling interval of Δt. P_{dci} is dc power for i_{th} sample.
Expected Energy annually	$E_{ex} = A \times H \times \eta_m \times PR$	kWh	Eex is the expected energy per annum, where A is area, H = annual solar irradiation, PR is performance ratio and η_m is module efficiency.
Performance output	$PR = \frac{Actual\ energy\ output}{Theoretical\ energy\ output}$	-	A index determine the performance of the experimental setup termed as performance ratio
Module Efficiency	$\eta_m = [P_{dc} / (G_{irr} \times A)]*100$	%	PV module with solar irradiation G_{irr} and module area as A m^2.
Theoretical Power [19]	$P_{Th} = P_{STC}[1-\beta(T_{mod} - T_{rf})]$	W	It is the power estimated theoretically considering module temperature T_{mod} and T_{rf}
Module Temperature [19]	$T_{mod} = T_{ab} + (T_{NOCT} - 20) \times (\frac{G_{irr}}{800})$	°C	To understand the effect rise in module temperature on power output. actual operating condition of PV panel.
Degradation Rate	$D_R = \frac{(P_{initial} - P_{final})}{P_{final} \times time} \times 100$	%	Degradation rate in power output with continuous operation and ageing of PV module calculated on annual basis.
Payback Period [20]	$P_B = \frac{C_i}{AS}$	Years	P_B is the time required to recover the initial investment from savings of revenue generated by solar PV setup. C_i is initial investment, AS is annual saving due to energy output by the setup.
End-of-Life (EoL) Estimation	$P_{N,out} < 0.8\ P_0$	Years	Number of years after which the normalized energy output drops below 80% of its initial value. P^N_{out} it output power in N^{th} year.

3.2. Scaling criteria

The transition from small scale PV systems to utility scale PV system significantly improves in solar energy deployment and also improves both technical and economic performance. Usage for small scale PV systems are in residential, laboratories, rooftops and where small loads are required, whereas utility scale PV systems are used for grid connected power generation systems. The system performance, payback period and EOL are the parameters which might not be much effected by interpolation scale. Therefore, a general but most versatile scale can resolve the issue of interpolation. The scaling factor (SFP) can be identified as (6), and therefore the scaled energy of 100 MW plant is obtained by (7). The economic analysis of both experimental setup and extrapolated plants can be obtained by payback given in Table I. The economic feasibility of the large rating plans is analysed by calculating net present cost with in the total life of the plant, evaluated by using (8). Another factor compares the generation economics is Levelized cost of energy (LCOE), it indicates the price of per unit energy generation with in the life time of the plant and is given by (9).

Power Scaling Factor (SFp) = Targeted Plant Size/Experimental set up Size (6)

$$Scaled\ Energy\ Generation\ (E_{sg}) = Energy\ generation\ Experimental\ setup \times (SF_P) \quad (7)$$

Net present cost $NPC = C_i + OMC + C_r - salvage\ value$ (8)

$$LCOE = \frac{Total\ lifetime\ cost}{Generated\ energy\ in\ life\ time} = \frac{NPC}{\sum_{i=1}^{N} E_{gi}} \quad (9)$$

where E_{gi} is the energy generation in the i_{th} year and N is the total number of years of working life of the PV plant. The annual revenue (AR) produced by utility scale PV plant can be given by (10).

$$AR = E_{gi} \times per-unit\ Tariff\ rate\ for\ i_{th}\ year \quad (10)$$

Thus, the methodology followed for this study is arranged as flow chart shown in Fig. 3.

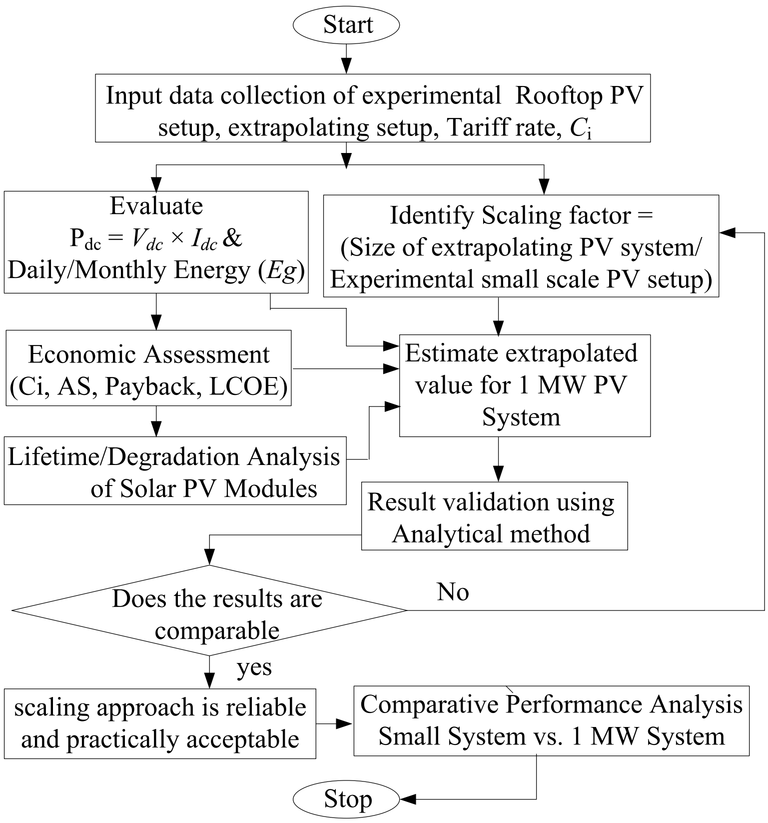


Fig. 3 Flowchart Technical and Economics analysis of small scale and extrapolated solar PV system

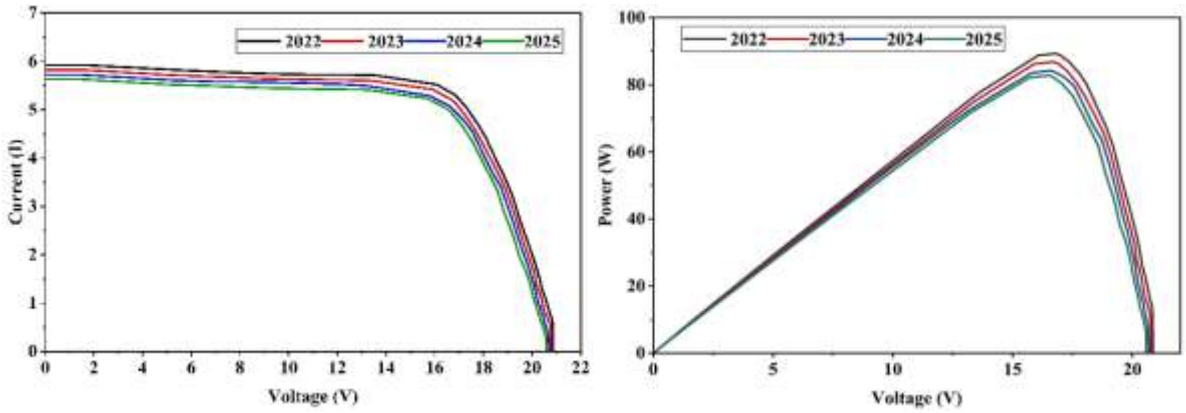
4. Results and Discussion

To evaluate how well the experimental setup performs year-by-year, a dynamic analysis of current-voltage (I-V), power-voltage (P-V) characteristics, and dynamics of power with temperature and irradiance is performed. Thereafter, a longitudinal comparison of theoretical and experimental power has performed. Based on the yearly energy practically available by the setup for the consecutive four years, degradation in energy output/performance and EoL prediction have been performed analytically for the PV module. At the end, the results are extrapolated for a 1 MW plant, and a size based economic comparison between the experimental setup and utility-scale plant has been studied. The analysis is based on measured data of the four consecutive years from 2022 to 2025 and is arranged in the following six sections.

4.1. Temporal analysis of I-V, P-V and Solar Irradiance Characteristics for the setup

In Fig. 4 (a) and (b), illustrating the I-V and P-V characteristics for the four consecutive years from 2022 to 2025 from the recorded values at nearly STC. Fig. 4(a) indicates the I-V characteristics in which the maximum output current lies in between 5.6A to 5.9A. However, the rated short circuit current for the panel used in this setup is 6.07 A at STC (1000 W/m² and 25°C). The same curve indicates that the maximum output voltage is in the range of 20.5 V to 20.8 V, whereas the rated open circuit voltage is 21.97 V. The difference in observed and rated values are due to the difference in operating conditions from STC.

Fig. 4(b) is the P-V curve indicating in which maximum output power decreases over the years progressively, with the values of 89.2 W, 86.8 W, 84.2 W and 82.8 W recorded for 2022,2023,2024 and 2025 respectively. The maximum power point occurs at a terminal voltage ranging between 16.82V to 16.53V. Over time, slightly reduction in open circuit voltage and PV system's power is observed which indicates the effects of degradation. It also affects the overall efficiency of PV module.



(a) (b)

Fig. 4 (a) and (b) I-V and P-V characteristics of PV module for consecutive four years

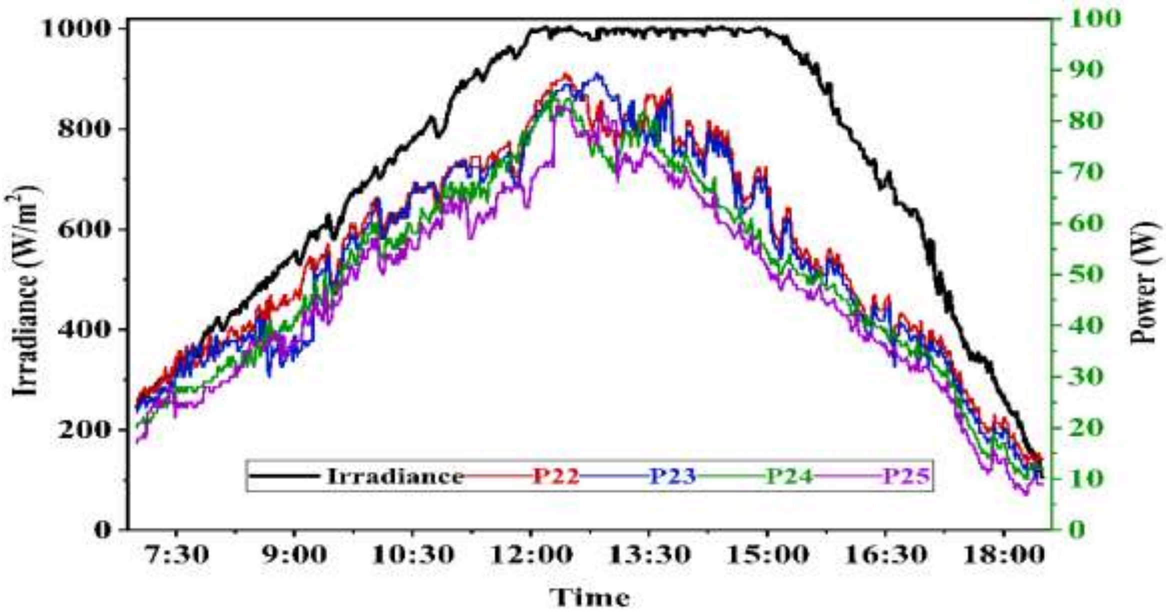
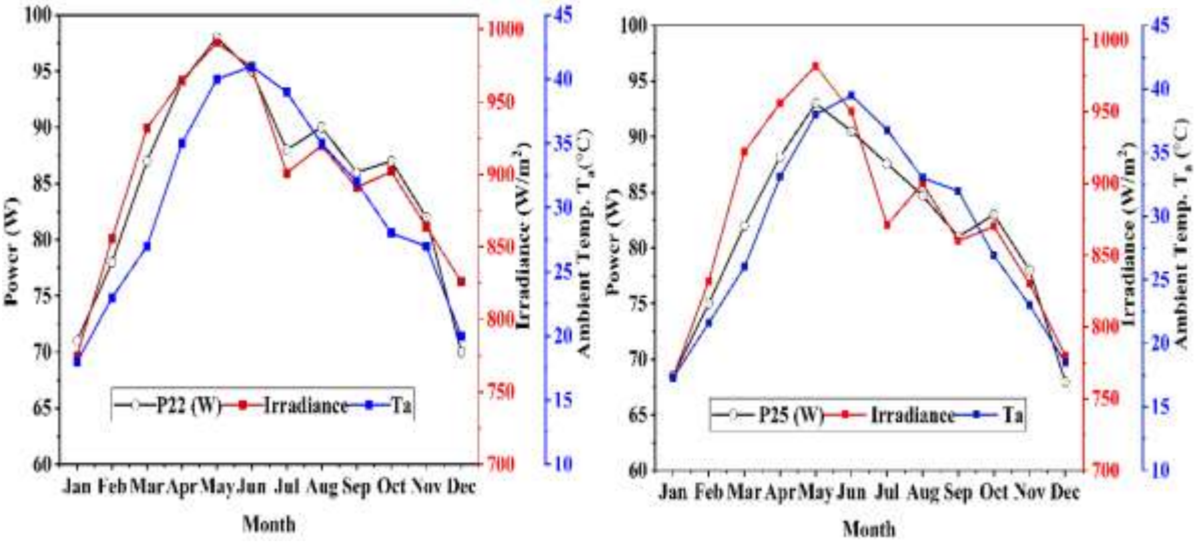


Fig. 5 Power variation with average annual irradiance

Fig. 5 represents the output power variation with average annual irradiance of PV module throughout the day for different four years. The irradiance profile forms a bell- shaped pattern, while other curves represent the corresponding output power for each year. At 7:00 AM, irradiance is 250W/m^2, output power lies around 18W to 26W. As the sun rises, irradiance increases and attains its peak i.e. 1000 W/m^2 between 12:30 PM to 2:00 PM. A similar increasing trend is observed in the output power.

During these years, around 1:00PM power output is high and recorded peak power values are 89.4W in 2022, 87W in 2023, 83.5W in 2024 and 82.6W in 2025. However, irradiance remains almost identical, gradual decrease in output power is evident each year. This reduction reflects the degradation of PV module and decline in its efficiency over time. The differences arise over years due to the environmental deterioration, system aging and temperature variations. However, after four years of operation power output began to decline, which indicates that system is undergoing declination due to environmental parameters and lack of maintenance.

4.2. Longitudinal analysis of power with ambient temperature and solar irradiance



(a) (b)

Fig. 6 Variation of power output, irradiance and ambient temperature of PV module in Year 2022 and 2025

Fig. 6 (a) and (b) shows the comparative analysis of power output, irradiance and ambient temperature between the initial year and after four years of operation. These parameters are main pointers for determining the performance assessment of 100W solar PV module. In both figures, solar irradiance rises from January and reaches its peak during May and June. Thereafter, irradiance level declined towards in December. Ambient temperature attains its peak point in June. This means that output power of PV module increases with irradiance level increases, but output power decreases due to high ambient temperature.

In fig. 6(a) Peak solar irradiance level is 991 W/m^2 in month of May 2022 while ambient Temperature is 40°C in the same month of May 2022. The output power rises 71 W to 98 W continuously from January 2022 to May 2022 because solar irradiance level increases as well as ambient temperature. In the month of June 2022, ambient temperature increases to 41°C but output power decreases around 95 W due to the declination in solar irradiance. As temperature rises, open circuit voltage reduces, narrows the semiconductor bandgap and lowers the overall efficiency of PV module. That's why maximum output power generated in May rather than June.

As we seen from Fig. 6 (b), output power increases from 68.5 W to 93 W with the rise in solar irradiance in month of January 2025 to May 2025. In the month of June 2025, when solar irradiance is high as well as ambient temperature, output power slightly reduces to about 90.5W as compared in May. Due to monsoon or cloud cover from July to Sep, irradiance level decreases, then output power also reduces. Efficiency improves in month of October to December due to lower temperature, but due to low irradiance it limits the output power. Reduction in output power shows the performance of PV module which suggests increased losses due to dust, system aging and losses in connection. In initial year 2022, output power shows better and closes to rated capacity, but after four years of operation in 2025, output power reduces due to environmental factors and additional losses as well as performance degradation.

4.3. Yearly Quantitative comparison of theoretical and experimental power for the setup

Fig. 7 illustrates the comparative analysis of the theoretical and experimental output power of 100W PV module from 2022 to 2025. This comparison shows how PV module's performance degraded under real time operating conditions as compared to its actual ideal performance. The theoretical power maintains value between 86.4W to 87.3W with slightly increasing trends over time. Under STC, assuming ideal solar irradiance, ambient temperature i.e. 25°C, and minimum losses in the system, this trend shows constant and slightly increasing expected performance. The slightly increase could be the result of better solar irradiance in this region.

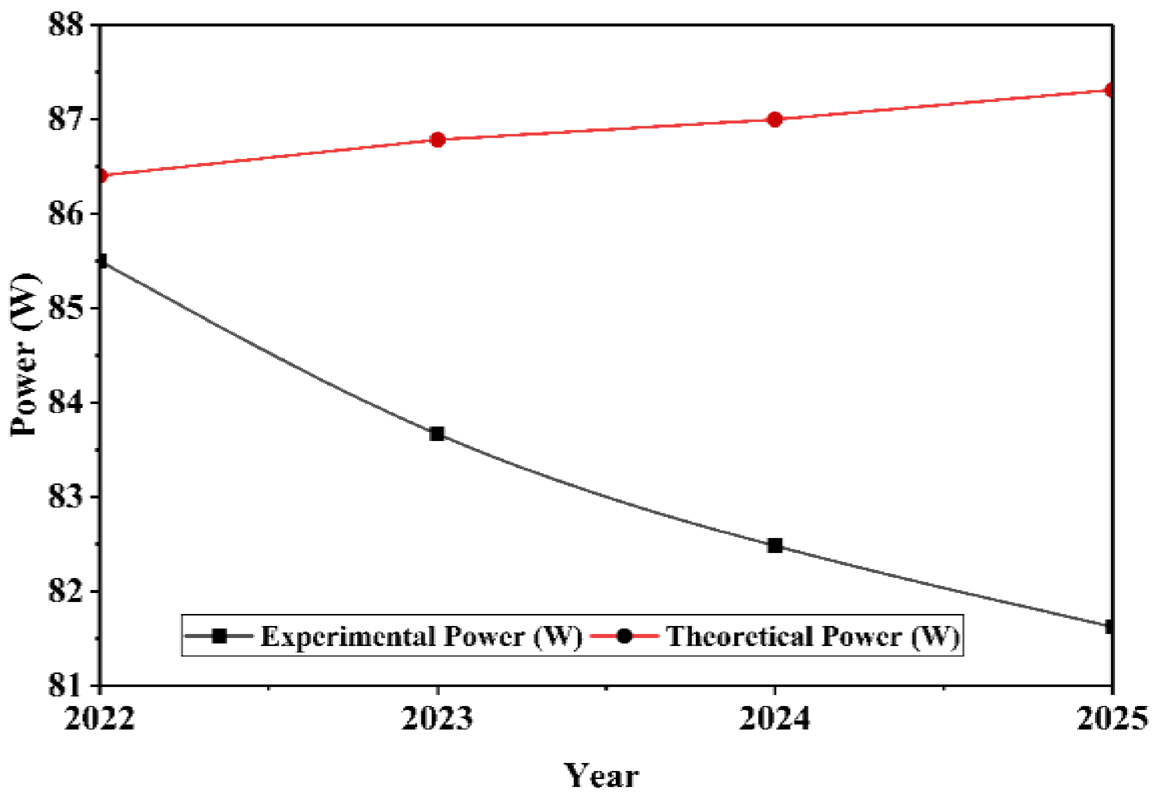


Fig. 7 Comparison of Theoretical and Experimental average annual output power

In experimental results, the average annual output power reduces from 85.5W in 2022 to 81.6W in 2025. The main reason of this reduction in actual output power over time are environmental factors and module degradation. These factors include Accumulation of dust or soiling effects, Thermal losses, deterioration of semiconductor materials and electrical losses. The growing difference between theoretical and experimental average annual output power over time shows the degradation in PV module performance. In year 2022, there is a slight difference between theoretical and experimental output power. However, after four years of operation in 2025, the interval is more apparent around 5W to 6W which shows the overall impact of environmental factors as well as system aging. This behaviour is essential for solar PV module's long term reliability over time and efficiency of solar PV system. It emphasizes how regular monitoring of performance, degradation analysis and regular maintenance are to precise energy output and economic viability forecasting.

4.4. Degradation analysis and EoL predication the setup

Fig. 8 shows the performance degradation trend of 100W PV module is constantly declined over time from year 2022 to 2025. Fig. 8(a) and (b) shows variations in PR and module efficiency trend. In year 2022, PR and module efficiency is 0.948 and 12.22% but after four years of operation, PR and module efficiency declined to 0.930 and 11.99% which indicates total reduction is approximately 1.81% in PR and average annual PR declination rate is 0.6% and total reduction in module efficiency is 1.90% and annual reduction in module efficiency is 0.63%, which shows the increase in system losses due to thermal impacts, environmental impacts, cell aging degradation, material degradation, discoloration, micro cracks, long exposure to high temperature and wiring defects etc. Experimental output power declined from 85.5W in 2022 to 81.63W in 2025. Similarly, yearly energy generation drops from 195.61 kWh to 186.68 kWh over the same period. These parameters show similar degradation rate of around 1.5% per year and sustaining a strong relationship between instantaneous output power and long term energy yield. Additionally, the existence of linear regression trends indicates that degradation exhibits a linear pattern which is beneficial for lifespan forecasting and predictive modelling.

Fig. 8(c) illustrates the degradation in experimental output power and annual energy generation from 2022 to 2025. In 2022, output power is high i.e. 85.5W, and decreases to 83.67W in 2023, followed by 82.48W in 2024 and finally observed 81.63W in 2025. During the study, total output power degradation is 4.53% and average annual decline is 1.51%. Similarly, annual energy generation trend also shown.

Annual Energy degradation linear trend shows with the help of given equation (11):

$$E_m = E_{out}(1 - D_R)^m \tag{11}$$

Where, E_m is energy after m years, D_R is degradation rate, E_{out} is initial energy output generation.
In 2022, annual energy generation is 195.61kWh which reduces to 191.37kWh in 2023, 188.63kWh in 2024 and 186.68kWh in 2025. This shows the overall energy degradation is 4.57% during 2022 to 2025 and average annual decline is 1.52%. This linear degradation trend shows uniformly degradation behaviour for both output power and average annual energy generation over the operating years.

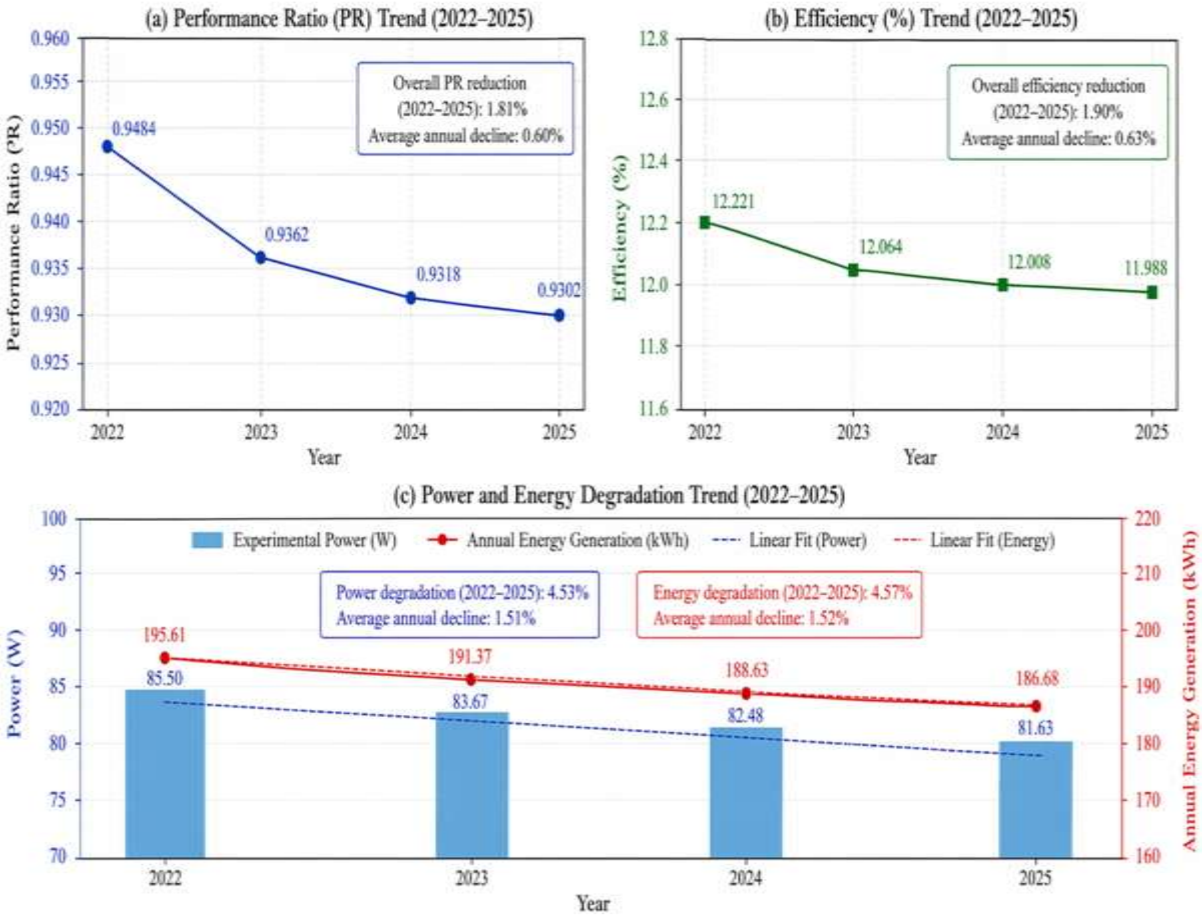


Fig. 8 Annually PV system Performance from 2022-2025 (a) Decline in Performance Ratio (b) Variation in Module efficiency over time (c) Combined trend of output power and annual energy generation with linear regression line

Overall, degradation rates which has been observed are slightly greater than the standards probably as an effect of localized environmental factors like dust accumulation, ambient temperature. In spite of this, system operates steadily with no significant fluctuations in performance which suggests consistent long term performance. This system aging behaviour shows no major faults but it shows healthy but aging PV system. These results are essential for economic analysis because they offer end of life estimation for small scale and utility scale systems and constant reduction in energy output directly affects the payback period and revenue generation. At 1.5% yearly degradation, after 20 years' system retains 80% output.
Fig. 9 indicates the comprehensive performance economic analysis of 100 W PV system integrating the performance degradation assessment, payback period and end-of-life estimation over 25 years of period. This analysis reveals annual energy generation trends under different degradation scenarios shows 0.5% per year under NREL, 1% per year under IEC upper limit and 1.5% per year as our experimentally observation along with data measured for 2022-2025. Higher degradation rate reveals earlier system aging and reduction in operational life.
The EOL of PV system is considered when annual energy generation decreases to 80% of the initial energy output. Initial annual energy generation is 195.6kWh/year then 80% EOL becomes 156.5kWh/year. Due to these observed parameters, EOL earlier than standard benchmarks. As compared to standard benchmarks, EOL results in an earlier to around 15 to 16 years at 1.5% per year degradation rate. This operational

lifetime is lower than the expected lifetime. The results clearly indicate that increased degradation reduces the useful operating life of the PV system.

The economic analysis explains the influence of degradation on long term financial performance. The cumulative cash flow at 1.5% per year degradation rate indicates payback period of approximately 5 years with initial system installation cost is around Rs.6000/- while tariff is considered as Rs.7/kWh. During initial five years, project remains in the cost recovery stage. After five years, system starts yielding positive economic returns and continuously increasing in cumulative savings and reaches approximately Rs.12000/- after 25 years of operation. After degradation effect, system consider NPV is Rs.2800/- indicates that PV installation remains economically viable over its lifetime. The comparison with standard degradation trends highlights the importance of environmental factors, long term energy yield and system maintenance in long term PV performance.

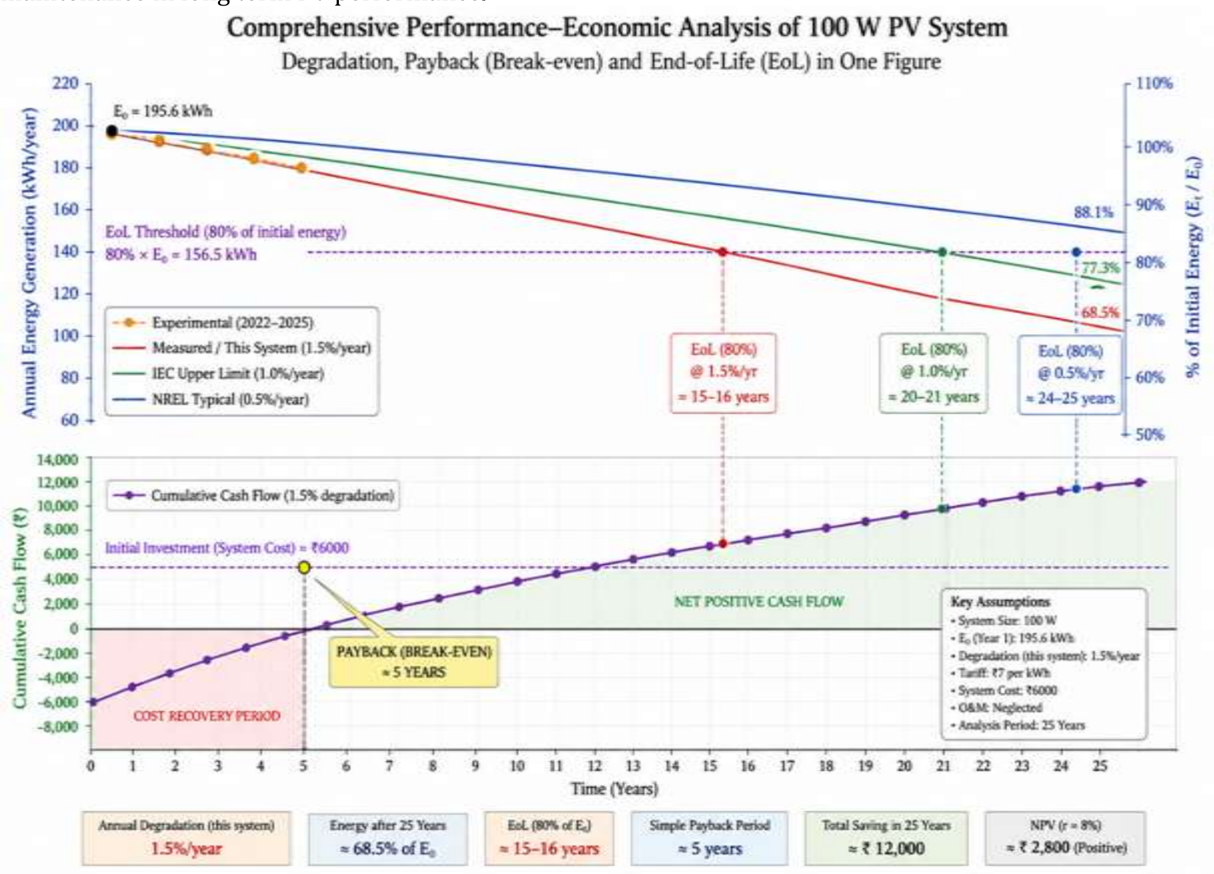


Fig. 9 Integrated techno-economic analysis of 100 W PV system

Possible reasons for performance degradation in our field study are high ambient temperature region, UV exposure and system aging, operation and maintenance, dust, soiling accumulation and inefficiencies of small scale systems. According to NREL median degradation rate is around 0.5% per year and IEC suggests 1% per year. After 25 years of operation, when degradation rate is 0.5% system retains output 88 to 90%, at 1% degradation rate, system retains output 75 to 80% and at 1.5% degradation rate per year system drops to output 68 to 70% of its initial performance.

4.5. Extrapolation of experimental results to the Utility scale PV system

In this Fig. 10 there is a comparison between 100W experimental PV system and its utility scaled 1MW equivalent PV system over a period from 2022 to 2025. In Fig. 10(a), energy generation shows a linear relationship between system capacity and annual energy output. In 100W PV system, annual energy generation shows a declined indicator approximately 195.6kWh in 2022 to 186.7kWh in 2025. This reduction occurs due to environmental factors, dust accumulation and aging in material etc. When same system scaled to 1MW utility scale PV system, annual energy generation increases from 1956 MWh to 1866 MWh from a period of 2022 to 2025. After scaling, energy output scales linearly with system capacity while reflects a small declination over time due to performance degradation.

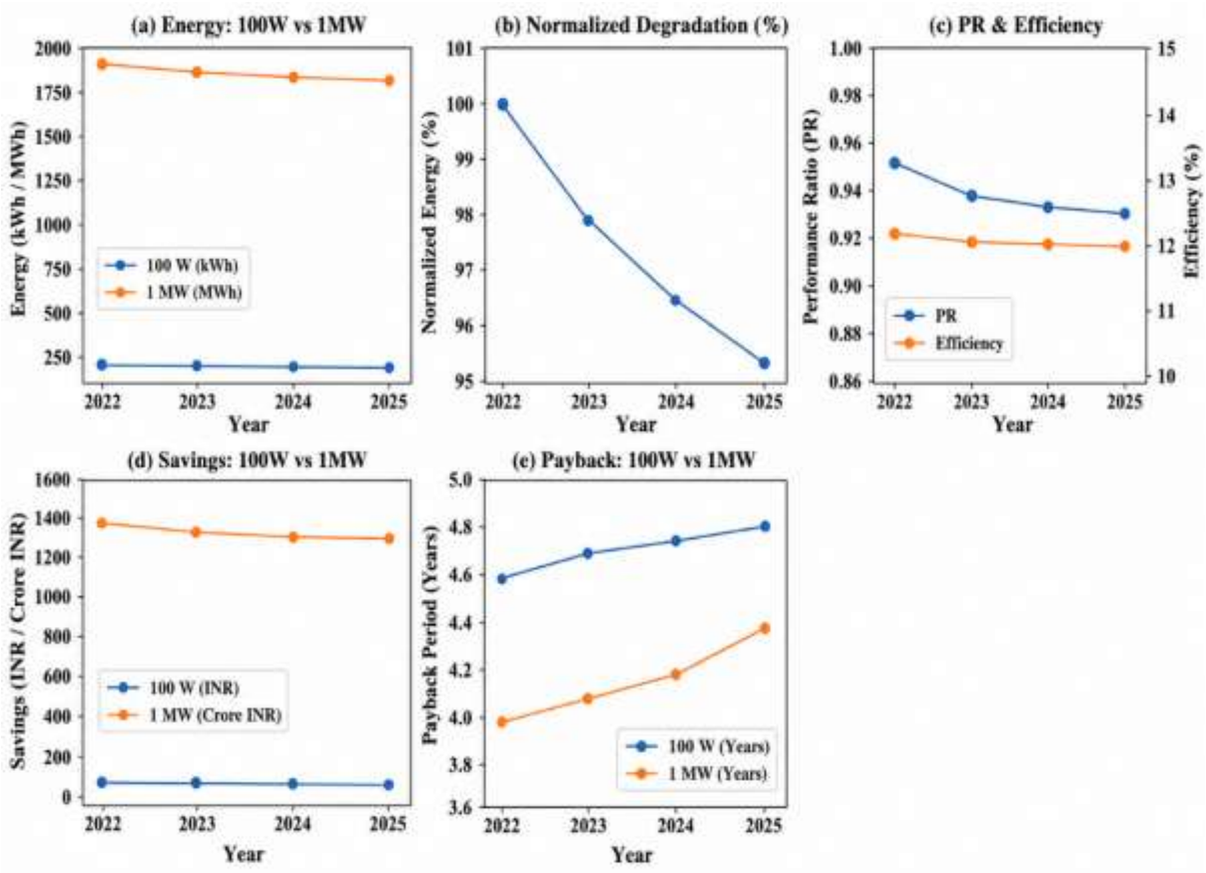


Fig.10 Comparative analysis of 100W PV system to 1M PV system

Fig. 10(b) shows normalized degradation of the system provides a scale independent performance assessment. Normalized energy drops from 100% to 95.4% approximately over a time period from 2022 to 2025 which indicates average degradation rate is about 1-1.5% over four years. In this, both systems 100W and 1MW are expected to identical degradation behaviour under identical environmental factors and operating conditions. Variation of PR and efficiency as shown in Fig. 10(c). According to the results, PR drops from 0.94 to 0.93 from initial state to after four years of operation. Similarly, efficiency drops down minimally from 12.22% to 11.99% due to aging of system components. At utility scale PV system, these variations are improved and maintained due to advanced technologies in inverter, better thermal management and system design.

In fig. 10(d) savings of 100W PV system decreases from Rs.1369/- to Rs.1306/- from 2022 to 2025. When this system scaled to utility PV system savings increases to Rs.1.37 crore in 2022 and reduces to Rs.1.31 crore in 2025. Advantage of scaling shows proportional increase in savings with slight degradation in performance behaviour.

Payback period variation between 100W and 1MW shown in Fig. 12(e). In this, payback period in 100W system increases slightly over time whereas in 1MW system achieves shorter payback period due to reduction in cost per watt, high annual revenue, higher energy production and economies of scale.

4.6. Size based economic comparison for the solar PV setups

While performing the experiment, some physical or mechanical factors that have come to light are those due to which our system is moving towards degradation are shown in Table 4.

Table 4: Comparison from small scale PV system to utility scale PV system

Parameter	Small scale PV system (100 W)	Utility scale PV system (1 MW)
Capacity	Watt/kW	MW/GW
Cost per Watt	High	Low
Performance Ratio	0.7 – 0.8	0.8 – 0.9
Degradation	Higher	Lower
Payback	5 – 8 years	3 – 5 years
Maintenance	Low	High

Energy output	Very Low	Very High

Environmental factors are the main factor influencing of PV output is the intensity of solar irradiance, however if long term irradiance change is not appropriately normalized, it might complicate estimates of degradation. Overall energy yield and the short circuit current must be influenced by the fluctuations of irradiance. For polycrystalline silicon PV modules, range of temperature coefficients are -0.3%/degree Celsius to -0.5%/degree Celsius. Dust accumulation and humidity are the major cause to reduce the efficiency of PV modules.

5. Conclusion

The purpose of the study shows a techno economic assessment of 100W PV system with focus on performance assessment, payback period, life cycle cost behaviour and end-of-life analysis followed by methodical scaling of small scale PV system to utility scale PV system. The findings demonstrate that small scale PV systems can reach reasonable payback period under ideal conditions, however effective payback period increases when practical operating factors like yearly performance degradation are taken into account.

Based on results, it observed 1.5% per year degradation rate in efficiency and PR which affects the annual energy generation and financial outcomes. Basically, these results also affect the lifecycle assessment. On the basis of these results, the EOL of PV system was predicted to occur within nearly 15 to 16 years when output reduces to 80% of its initial capacity. Even with degradation effects, system remained economically viable with payback period of nearly 5 years and positive long-term cumulative savings.

This also indicates that when PV systems continue to operate after payback period their economic viability declines over time due to reduction in energy yield and possible increases in maintenance requirement.

When 100W system is extended to utility scale PV system, there is some improvement in economic viability, system efficiency improves and Levelized cost of energy also reduced, reduction in maintenance cost per unit energy generated. Utility scale PV systems benefits from economics of scale, shorter payback periods and better lifecycle performance as compared to small scale PV system.

Overall, findings show that small scale PV systems are well suited for residential applications and localized energy generation whereas utility scale PV system offers large scale energy generation, and long term economic and operational benefits. However further research work should focus on advanced degradation mechanism, improvement in long term sustainability, recycling strategies, real time variations in the climate and support policymakers and decisions in large scale solar energy deployment.

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