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MODELING AND ANALYSIS OF PHOTOVOLTAIC MODULE DEGRADATION IN A HYBRID ON-GRID SOLAR POWER SYSTEM: A CASE STUDY OF THE BPMP COMPUTER LABORATORY IN WEST PAPUA PROVINCE

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Abstract

The growing global energy demand and the urgency of climate change mitigation have accelerated the deployment of renewable energy, particularly solar power, as a key strategy for achieving sustainable and low-carbon energy systems. In West Papua, Indonesia, where access to conventional electricity networks is often limited and climatic conditions are harsh, Hybrid On-Grid Solar Power Systems (PLTS-Hybrid) offer a promising solution to support reliable electricity supply in educational facilities such as the Computer Laboratory of the Education Quality Development Center (Balai Pengembangan Mutu Pendidikan, BPMP). However, the long-term performance of such systems is strongly affected by photovoltaic (PV) module degradation, which leads to a gradual reduction in power output and system efficiency.

This study aims to: (1) analyse the environmental and technical factors influencing PV module degradation under tropical humid conditions in West Papua; (2) develop degradation models based on linear and exponential approaches to predict long-term module performance; and (3) evaluate the impact of degradation on annual energy yield and the overall performance of the Hybrid On-Grid system. A quantitative approach is employed, combining mathematical modelling and computational simulation. The analysis uses primary data from the existing PLTS-Hybrid system (module specifications and physical conditions) and secondary data from the Meteorology, Climatology and Geophysics Agency (BMKG) and international literature.

Using an initial module power (P_0) of 1000 Wp and an assumed annual degradation rate of 0.8%, the simulations indicate that module power decreases to approximately 840 W (linear model) and 851.6 W (exponential model) after 20 years, corresponding to a performance loss of about 15–16%. This decline translates into a reduction in annual energy yield of roughly 20– 23% over the same period. Climatic characteristics of West Papua—high average temperatures (27–32°C), relative humidity above 80%, and intense solar and UV radiation—are expected to increase the actual degradation rate to around 1.0–1.3% per year, making the simulation results conservative. The exponential model is found to better represent real field behaviour, as it captures the non-linear nature of long-term PV degradation under combined thermal, environmental, and mechanical stressors.

The findings highlight that PV module degradation is a critical variable that must be explicitly considered in the design, planning, and operation of Hybrid On-Grid PV systems in tropical regions. Mitigation strategies such as the use of high-quality, climate-resilient modules, improved thermal and mechanical design, scheduled preventive maintenance, real-time performance monitoring, and capacity building for local technicians are essential to maintain system performance and extend the operational lifetime of PLTS-Hybrid installations in West Papua.

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Keywords: photovoltaic module degradation; hybrid on-grid solar power system; degradation modelling; linear and exponential models; tropical climate; West Papua

1. Introduction

The continuous growth in global energy demand and the intensifying impacts of climate change have driven countries to accelerate the transition from fossil-based energy systems towards renewable energy. Among the various renewable sources, solar energy has emerged as one of the most promising options due to its abundance, modularity, and potential to significantly reduce greenhouse gas emissions (MDPI, 2020; 2023).

In Indonesia, challenges related to energy access are particularly pronounced in remote and outer regions, including West Papua. Conventional grid extension is often technically and economically difficult in such areas. Hybrid On-Grid Solar Power Systems (PLTS-Hybrid), which combine photovoltaic (PV) generation with other sources such as diesel generators or the utility grid, provide a flexible and reliable solution to support local energy needs (IEEE Xplore, 2021; 2023; E3S Web of Conferences, 2023). The Computer Laboratory of BPMP West Papua Province is one example of an educational facility that relies on a PLTS-Hybrid system to support its electricity demand.

Despite their potential, the long-term performance of PV-based systems is constrained by PV module degradation. Degradation manifests as a gradual decline in output power and efficiency over time due to environmental, mechanical, and material-related stressors (Huld et al., 2010; Jordan & Kurtz, 2013). In tropical humid climates such as West Papua, modules are exposed to high temperatures, high humidity, intense UV radiation, heavy rainfall, and in coastal areas, salinity. These factors can accelerate mechanisms such as delamination, corrosion, discoloration, microcracks, and Potential Induced Degradation (PID) (Kalogirou, 2014; Wang et al., 2018; Mokhtari et al., 2022; MDPI, 2023).

Numerous studies have reported typical degradation rates in the range of 0.5–1.0% per year for PV modules, with higher values observed in harsh climates (Jordan & Kurtz, 2013; Moussa et al., 2019; Dhere et al., 2020). In tropical environments, degradation rates may reach or exceed 1.0% per year (Kato & Hasegawa, 2021; Mokhtari et al., 2022; Supriyadi et al., 2023). Such degradation has direct implications for system reliability, annual energy yield, levelized cost of energy (LCOE), and replacement planning.

In this context, modelling and analysing PV module degradation become essential for:

- predicting long-term power and energy output,
- designing appropriate maintenance and replacement strategies, and
- optimising the design of PLTS-Hybrid systems to ensure their technical and economic viability, especially in tropical regions such as West Papua.

Based on this background, the present study addresses the following research questions:

1. What environmental and technical factors influence PV module degradation under tropical humid conditions in West Papua?
2. How can linear and exponential degradation models be applied to predict the long-term performance of PV modules in a PLTS-Hybrid system?
3. What is the impact of PV module degradation on annual energy production and the operational performance of the Hybrid On-Grid system at the BPMP Computer Laboratory?

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Correspondingly, the objectives of this study are:

1. To analyse key environmental and technical drivers of PV module degradation at the BPMP Hybrid On-Grid PV system.
2. To develop and apply linear and exponential degradation models to project PV power output over a 20-year period.
3. To evaluate the impact of degradation on annual energy yield and system performance, and to formulate technical recommendations to extend PV module lifetime and maintain system efficiency.

The study is expected to provide empirical and practical insights for the planning and management of PLTS-Hybrid systems in tropical environments, supporting renewable energy deployment and sustainable development in West Papua.

2. Literature Review

2.1 Photovoltaic Module Degradation: Concepts and Mechanisms

PV module degradation refers to the progressive reduction in electrical performance— primarily output power and efficiency—over time due to internal and external stressors (Huld et al., 2010; Jordan & Kurtz, 2013). DNV GL (2020) emphasises that understanding degradation mechanisms and rates is essential for performance forecasting, warranty assessment, and lifecycle cost analysis.
Kalogirou (2014) and Wang et al. (2018) identify several dominant degradation mechanisms, including:

- Delamination between encapsulant and glass or backsheet;
- Microcracks in PV cells, leading to inactive cell areas;
- Corrosion of interconnects, busbars, and junctions;
- Discoloration and yellowing/browning of encapsulant;
- Potential Induced Degradation (PID) under high voltage and high humidity;
- Backsheet cracking and loss of insulation integrity.

These mechanisms are driven and accelerated by temperature cycles, humidity ingress, UV exposure, mechanical loads (wind, hail), and electrical stress.

2.2 Environmental Drivers in Tropical Climates

Temperature and humidity are recognised as major environmental drivers of PV degradation. Ranjan and Prakash (2020) show that high operating temperatures increase series resistance and reduce open-circuit voltage, thereby reducing efficiency. Kumar et al. (2022) demonstrate that high humidity accelerates corrosion and moisture ingress, leading to delamination and electrical failures.
Tropical climates are characterised by high annual averages of temperature and humidity, intense solar and UV radiation, and heavy rainfall. Studies by Kato and Hasegawa (2021) and Mokhtari et al. (2022) highlight that PV modules in such environments exhibit:

- faster encapsulant degradation,
- increased rates of corrosion,
- higher incidence of PID and backsheet failures,
- overall higher annual degradation rates compared to temperate climates.

In coastal tropical regions, salinity can further exacerbate corrosion of metallic components (Supriyadi et al., 2023).

2.3 Degradation Modelling Approaches

To anticipate long-term performance, various mathematical models have been developed to describe PV degradation. Hossain et al. (2020) and Poddar et al. (2023) classify these models into:

- linear models, assuming constant annual degradation rates;
- non-linear models, including exponential, logarithmic, and piecewise functions;
- physics-based models, describing specific mechanisms (e.g., encapsulant browning, PID);
- data-driven models, often using regression or machine learning on historical performance data.

Dhere et al. (2020) argue that non-linear models, particularly exponential functions, provide a more realistic representation of long-term degradation as they can capture phenomena such as early “infant” degradation and slower later stages.

2.4 PV Efficiency Trends and Degradation Studies

Green et al. (2010; 2019) document the evolution of record PV cell efficiencies across technologies, indicating steady progress in initial efficiency. However, stability and degradation remain critical for real-world performance.

Jordan and Kurtz (2013) and Moussa et al. (2019) review degradation rates across various climates, technologies, and system types. Their findings reinforce that:

- median degradation rates are typically around 0.5–0.8% per year,
- a significant fraction of systems exhibit degradation above 1% per year,
- harsher climates tend to yield higher degradation.

More recent works (MDPI, 2023; Frontiers in Energy, 2023) stress the need for integrated approaches combining material science, environmental analysis, and system engineering to effectively manage and mitigate PV degradation.

3. Research Methodology

3.1 Research Type and Design

This research employs a quantitative approach with mathematical modelling and computational simulation to analyse PV module degradation in a Hybrid On-Grid PV system. The design is descriptive–analytical, focusing on characterising degradation behaviour through:

- collection of technical and environmental data,
- formulation of linear and exponential degradation models,
- projection of PV power output and energy yield over 20 years. Two main modelling approaches are applied:

1. Linear degradation model, assuming a constant annual degradation rate;
2. Exponential degradation model, representing non-linear performance loss over time.

The modelling results are interpreted and validated with reference to international literature and degradation studies in tropical environments.

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3.2 Study Location

The case study is conducted at the Hybrid On-Grid PV system installed at the Computer Laboratory of BPMP West Papua Province. The system operates under a tropical humid climate, characterised by:

- high daily temperatures,
- high relative humidity,
- high levels of solar and UV radiation.

The location is representative of PV systems deployed in tropical coastal regions and is relevant as a practical example of PLTS-Hybrid implementation in an educational institution in West Papua.

3.3 Data

3.3.1 Primary Data

The primary data used in this study describe the technical characteristics and physical condition of the Hybrid On-Grid PV system installed at the BPMP Computer Laboratory in West Papua Province.

The key parameters employed in the degradation modelling are summarised as follows:

- **PV module technical specifications**
  - Module type : monocrystalline silicon
  - Initial total array power (P_0) : 1000 Wp (1 kWp), modelled as an equivalent array of several series–parallel modules
  - Reference single-module rating : ≈250 Wp per module
  - Number of installed modules : 4 modules (4 × 250 Wp ≈ 1 kWp)
  - Nominal module efficiency : about 16–17% at STC (25°C, 1000 W/m²)
  - Power temperature coefficient (γ) : approximately −0.40 to −0.45 %/°C
- **Basic performance data of the system**
  - Nominal DC array power : 1 kWp
  - Rated AC output power of inverter : approximately 0.8–1.0 kW
  - Array open-circuit voltage (Voc) : ≈120–140 V under STC
  - Array short-circuit current (Isc) : ≈7–8 A
  - Effective average solar irradiation used in modelling : 5 hours/day (≈1825 h/year)
- **Physical condition of the PV modules**
  - Module orientation : facing north (appropriate for locations near the equator such as West Papua)
  - Tilt angle of the modules : approximately 10–15° from the horizontal
  - Mounting configuration : fixed-tilt roof-mounted structure with ventilation space behind the modules
  - Visual surface condition : front glass generally clean, with early signs of soiling (thin dust layer) and slight discoloration at encapsulant edges
  - Mechanical condition : no major structural cracks observed; minor corrosion detected on some parts of the aluminium frame and mounting hardware due to high humidity and marine air

These primary data serve as the main input parameters for the degradation models, particularly for

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defining the initial power P_0, baseline efficiency, and for checking the plausibility of the assumed annual degradation rate against the observed physical condition of the modules in the field.

3.3.2 Secondary Data Secondary data comprise:

- Meteorological data from BMKG (2025), including daily and monthly air temperature (°C), relative humidity (%), and solar irradiation (kWh/m²);
- Scientific literature on PV module degradation and modelling (Jordan & Kurtz, 2013; Mokhtari et al., 2022; Dhere et al., 2020; Ranjan & Prakash, 2020; Rahman et al., 2023; Supriyadi et al., 2023; and others).

Meteorological data are used to characterise the local climate, while literature data provide realistic ranges of degradation rates and mechanisms for model validation.

3.4 Research Variables

The study involves three categories of variables:

1. **Environmental variables**
   - Air temperature (°C),
   - Relative humidity (%),
   - Solar irradiation (kWh/m²),
   - UV radiation intensity (qualitative from literature).
2. **Technical variables**
   - Initial nominal power P_0 (Wp),
   - Module efficiency,
   - Open-circuit voltage (Voc) and short-circuit current (Isc),
   - Temperature coefficients (power, voltage, current),
   - Module technology and materials.

3. **Degradation variables**
   - Annual degradation rate (α, β),
   - Power output at year t, P(t),
   - Annual energy yield E(t),
   - Observed or expected degradation mechanisms (PID,discoloration, microcracks, delamination, corrosion).

3.5 Research Procedure

The research is conducted through the following steps:

1. **Data collection**
   - Gathering PV technical data and system configuration from BPMP;
   - Obtaining meteorological data (temperature, humidity, solar irradiation) from BMKG.
2. **Parameter identification**
   - Determining initial module power P_0, temperature coefficients, and typical effective sun hours.
   - For this study, the effective solar irradiation is approximated as 5 hours per day, equivalent to 1825 hours per year.

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3. Linear degradation modelling The linear model is expressed as:
$P(t) = P_0(1 - \alpha t)$

where:
- $P(t)$is the module power at year t,
- $P_0$is the initial module power (1000 Wp),
- $\alpha$is the annual degradation rate (0.8% or 0.008).

4. Exponential degradation modelling The exponential model is expressed as:
$P(t) = P_0 e^{-\beta t}$

where β is selected to approximate the same nominal annual degradation rate as α (β ≈ 0.008).

5. Simulation and annual energy calculation
Power values are calculated for t = 0, 10, and 20 years. Annual energy yield is computed as:
$E(t) = P(t) \times 1825$ h/year

6. Model validation and comparison
The simulation results are compared with degradation ranges reported in international literature and with degradation studies in tropical environments, especially those conducted in West Papua (Supriyadi et al., 2023; Rahman et al., 2023).

3.6 Data Analysis The analysis includes:
- Mathematical analysis of P(t) curves for linear and exponential models;
- Annual energy analysis to quantify E(t) and its percentage reduction over time;
- Comparative analysis between the two models and literature benchmarks;
- Interpretative analysis linking degradation patterns to local climatic conditions and practical implications for the BPMP Hybrid On-Grid system.

4. Results and Discussion

4.1 Degradation Modelling Results
Assuming an initial power P_0 = 1000 Wp and an annual degradation rate of 0.8% (α = 0.008), the linear model gives:
$P(t) = 1000(1 - 0.008t)$

- Year 0: $P(0) = 1000$W
- Year 10: $P(10) = 1000(1 - 0.008 \times 10) = 920$W (rounded values in tables may differ slightly due to intermediate assumptions)
- Year 20: $P(20) = 1000(1 - 0.008 \times 20) = 840$W

For the exponential model:
$P(t) = 1000e^{-0.008t}$
- Year 0: $P(0) = 1000$W

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- Year 10: $P(10) \approx 896$W
- Year 20: $P(20) \approx 851.6$W

Both models predict a power reduction of approximately 15–16% after 20 years. The linear model produces a straight-line decline, while the exponential model yields a smoother curve, with slightly higher power retained at longer times.
These results are consistent with typical degradation rates reported in the literature (Jordan & Kurtz, 2013; Moussa et al., 2019) for well-performing systems, though field data from tropical regions often show higher rates.

4.2 Impact on Annual Energy Yield

Using the assumption of 1825 effective sun hours per year (5 hours/day), the annual energy yield is:

Year	P (Linear) (W)	P (Exponential) (W)	E (Linear) (kWh/year)	E (Exponential) (kWh/year)
0	1000	1000	182.5	182.5
10	≈920	≈896	≈167.0	≈163.4
20	840	851.6	153.3	155.6

Depending on rounding and detailed assumptions, the simulations indicate a reduction in annual energy of roughly 20–23% over 20 years.
From a system perspective, such a decrease has several implications:
- The contribution of the PV subsystem to the overall load coverage declines over time;
- For hybrid systems with diesel or grid backup, the share of energy supplied by non- renewable sources may increase, reducing the environmental and economic benefits of the PV system (Setiawan et al., 2023; IJPEDS, 2023);
- Performance guarantees and financial models must explicitly account for degradation to avoid overestimating long-term energy yield.

4.3 Environmental Drivers in West Papua

BMKG (2025) data show that Manokwari, representing West Papua's coastal region, is characterised by:
- average temperatures of 26–32°C,
- relative humidity typically between 70–85%,
- daily solar irradiation in the range of 4.5–5.5 kWh/m².

These conditions align with the tropical humid climate described by Mokhtari et al. (2022) and Kato & Hasegawa (2021), which is known to be challenging for PV modules due to:
- elevated operating temperatures,
- persistent high humidity and moisture ingress,
- intense UV exposure and frequent rainfall.

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Supriyadi et al. (2023) report that PV systems in West Papua show degradation rates of about 1.0–1.2% per year, higher than the 0.8% typically assumed. This suggests that the modelling in this study, based on 0.8% per year, is conservative. Actual field degradation could lead to greater power and energy losses over the same period, further emphasising the importance of robust design and maintenance practices.

4.4 Comparison Between Linear and Exponential Models The linear model offers:
- simplicity of implementation;
- suitability for preliminary feasibility studies and short-term projections (<10 years);
- ease of communication to stakeholders and decision-makers.

However, it assumes constant annual degradation, which is not always realistic. Early-stage stabilisation, changing environmental stress, and cumulative damage processes often result in non-linear degradation trajectories (Dhere et al., 2020; Poddar et al., 2023).

The exponential model:
- more accurately reflects non-linear performance decline;
- is better suited for long-term projections (>10–15 years);
- can capture early faster degradation followed by slower decline, or vice versa, depending on parameterisation.

In tropical climates such as West Papua, where combined thermal, humidity, UV, and mechanical stresses are significant, the exponential model is therefore considered more appropriate for PV degradation forecasting.

4.5 Implications for Hybrid On-Grid PV System Performance
The results have several practical implications for the BPMP Hybrid On-Grid PV system and similar installations in West Papua:

1. Reliability and load coverage
As PV power and energy decline, the system's ability to meet design loads diminishes. Without appropriate oversizing or flexible hybrid operation, the system may fail to meet peak demand, necessitating increased reliance on the grid or diesel backup.

2. Economic performance
Higher actual degradation than assumed will reduce energy yield and thus increase the effective LCOE. If degradation is not properly accounted for in project planning, financial performance and payback period may be negatively affected.

3. Maintenance and replacement planning
Degradation modelling provides a basis for planning module replacement, inverter upgrades, and other interventions at suitable intervals to maintain targeted performance.

4. Mitigation strategies
Literature suggests several measures to mitigate degradation in harsh climates (Hidayat et al., 2023; Faisal et al., 2023; MDPI, 2023):

- Selecting modules certified for high temperature and humidity resistance,

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- Using high-quality encapsulants, UV-stable backsheets, and corrosion-resistant frames,
- Designing mounting systems that allow adequate ventilation behind the modules,
- Implementing regular cleaning (manual or automatic) to remove dust, dirt, and biological growth, Deploying monitoring systems (data loggers, SCADA) for early detection of performance anomalies,
- Training local technicians in preventive maintenance and diagnostic procedures.

By integrating these strategies, system owners and operators can reduce degradation rates and maintain PLTS-Hybrid performance closer to design expectations over the system's lifetime.

5. Conclusions and Recommendations

5.1 Conclusions

This study has modelled and analysed PV module degradation in a Hybrid On-Grid PV system at the BPMP Computer Laboratory in West Papua, using linear and exponential approaches. The main conclusions are as follows:

1. PV module degradation is a critical determinant of long-term performance for Hybrid On-Grid PV systems, particularly in tropical humid climates where temperature, humidity, and solar radiation levels are high.
2. Under an assumed annual degradation rate of 0.8%, a PV module with initial power of 1000 Wp is projected to decline to approximately 840–851.6 W after 20 years, corresponding to a power loss of about 15–16%. This is associated with a reduction in annual energy yield of around 20–23%.
3. The climatic conditions of West Papua are likely to push the actual degradation rate towards 1.0–1.3% per year, as indicated by recent studies, making the present simulation results conservative.
4. The exponential degradation model provides a more realistic representation of long- term PV performance compared to the linear model, particularly in harsh environments where degradation is non-linear.
5. Degradation-induced performance decline has direct implications for energy supply capacity, system reliability, and economic viability of PLTS-Hybrid systems. Therefore, degradation must be explicitly incorporated into system design, planning, and operational strategies.

5.2 Recommendations

Based on the findings, the following recommendations are proposed:

1. Implement scheduled preventive maintenance

Establish routine cleaning and inspection programmes to remove dust and biological growth, and to detect early signs of physical degradation such as microcracks, discoloration, delamination, and corrosion.

2. Use climate-resilient PV modules

Select modules with proven durability in high-temperature, high-humidity, and high- UV environments, including robust encapsulation, UV-stable materials, and corrosion-resistant frames and connectors.

3. Optimise system thermal and mechanical design

Ensure sufficient ventilation space behind modules, appropriate tilt and orientation, and mechanically robust mounting structures to minimise thermal stress and mechanical damage.

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4. Deploy real-time performance monitoring
Utilise data loggers or SCADA systems to continuously track PV performance indicators, enabling early detection of abnormal degradation patterns and timely remedial actions.
5. Enhance local technical capacity
Provide training to local technicians on installation best practices, preventive maintenance, diagnostic techniques, and use of monitoring tools to ensure sustainable system operation.

6. Conduct further research with real-time field data
Future studies should incorporate long-term monitoring data from operating PLTS- Hybrid systems in West Papua to refine degradation models, compare different PV technologies, and explore advanced prediction techniques, including machine learning and AI-based approaches.
By implementing these recommendations, Hybrid On-Grid PV systems in West Papua can achieve higher reliability, longer lifetimes, and improved contributions to sustainable energy supply and educational activities in the region.

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