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GLOSARIUM

Abbreviation	Term	Description
PLTS	PLTS (Solar Power Plant)	A power plant that uses solar energy as the primary source to generate electricity.
LCC	LCC (Life Cycle Cost)	The total cost associated with an asset, project, or product throughout its life cycle, including acquisition, operation, maintenance, and disposal costs.
LCOE	LCOE (Levelized Cost of Energy)	The average cost per unit of energy produced by a power plant over its full operational life. LCOE is used to compare the cost of power generation across different technologies.
PM	PM (Preventive Maintenance)	Maintenance that is performed on a scheduled and routine basis to prevent equipment or system failures.
CR	CR (Corrective Maintenance)	Maintenance that is performed after a failure or issue has occurred, with the aim of repairing and restoring the functionality of the equipment or system.
PdM	Pdm (Predictive Maintenance)	Maintenance that is based on the actual condition of the equipment, typically using data and analysis to predict when a component may fail so that maintenance can be performed before a failure occurs.
PLTS	Pembangkit Listrik Tenaga Surya or Solar Power Plant	It refers to a power generation system that utilises solar energy as the primary source to generate electricity. Solar energy is converted into electrical energy using solar panels (photovoltaics), which can

		then be used to meet the electricity needs of households, industries, or the general power grid.
SPWM	sinusoidal pulse width modulation	**(SPWM)** is a technique used in power electronics to control the output of inverters by generating a waveform that approximates a sine wave
SCR	silicon-controlled rectifier	(SCR) is a type of semiconductor device used to control and rectify electrical current in power electronics
IGBT	insulated-gate bipolar transistor	(IGBT) is a semiconductor device commonly used in power electronics for switching and amplifying electrical power.
AC	Alternating Current.	It refers to the type of electrical current in which the flow of electric charge periodically reverses direction
DC	Direct Current.	It refers to the type of electrical current in which the flow of electric charge is unidirectional, meaning it moves consistently in a single direction
IDR	Indonesian Rupiah,	which is the official currency of Indonesia.

CHAPTER I
THE PROBLEM

1.1. Rationale

Indonesia is located on the equator, between 6º North Latitude and 11º South Latitude, placing it in the tropical climate zone. In the tropical climate, particularly in Indonesia, measurements of solar radiation record values (Sun Peak Hours) or when the sun reaches a maximum intensity of 1000 W/m² for only a few hours. Because the solar radiation in Indonesia is mostly below 1000 W/m² or below (Sun Peak Hours), the economic impact of solar photovoltaic operations is significant during planning and operation [1]. Based on measurements from January to August 2024, the value of Global Horizontal Irradiance (GHI), or the total amount of solar radiation falling on a flat (horizontal) surface, reached a maximum intensity of 1000 W/m² at the research location, which was only achieved for 3 to 4 hours. The value of Sun Peak Hours at 1000 W/m² is the optimal solar radiation intensity expected for solar power plants. The solar power plant at the research site is located in a tropical climate and has been producing energy since October 2015, operating for nearly eight years.

Therefore, this research will begin from a different perspective to understand the economic impact of operation-based maintenance on photovoltaic solar panels.

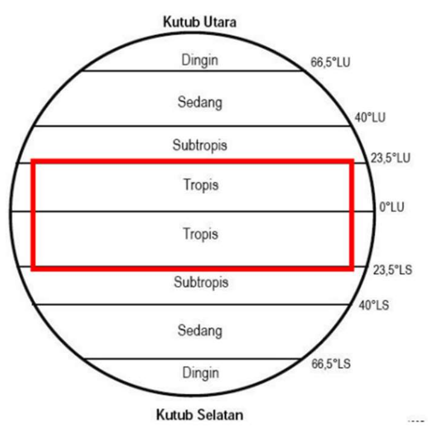

Figure 1.1 Solar Climate [2]

Solar power plants are considered low maintenance or require routine maintenance (preventive maintenance). This study comprehensively analyzes the impact of maintenance methods on the costs required for solar power plant maintenance. According to the literature [3], there are four cost management methods: activity-based costing, life cycle costing, target costing, and just-in-time costing. In this study, the method used is the life cycle cost (LCC) analysis. There are four cost management methods, one of which is the Life Cycle Costing

Method, consisting of three process stages: life cost planning, life cost analysis preparation, and life cost implementation and monitoring. In this study, the Life Cycle Cost Method is applied in the implementation and monitoring stages to continuously monitor an asset's actual performance, identify areas for cost-saving, and provide feedback for future life cost planning activities. LCC aims to control the initial costs and future costs required over a specific period or lifespan [4].

This study is one of the research efforts on solar power plants. It evaluates the performance of solar power plants, particularly by assessing the production results against the maintenance performed throughout their life cycle. Based on the initial project plan for the selected case study, the 1 MWp solar power plant requires a cost of USD 22 per kWp per year without specifying the type of maintenance required. Therefore, the research focuses on analyzing and identifying effective maintenance scenarios with cost efficiency that can maximize solar power plant production. In this study, the production projections consider yield reduction due to solar module degradation and solar power plant health based on the maintenance performed.

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This research utilizes data from a solar power plant that has been operational for eight years and has undergone maintenance to ensure continuous operation. The study employs the Life Cycle Cost (LCC) method, where the life cycle costs include investment and actual maintenance costs for the solar power plant that has been in operation for eight years. Three scenarios are used in this study. The first scenario evaluates the plant's performance based on the initial potential when it was constructed.

The second scenario uses actual production data but with low maintenance, meaning there are no costs for replacing materials or components when failures occur. The production level reflects the condition of the equipment after more than five years of operation. This scenario may have the lowest operational costs compared to the other two scenarios despite a decline in production due to equipment degradation or failures. In this scenario, no expenses are incurred for replacing damaged equipment; only routine maintenance, such as solar panel cleaning, is performed.

The third scenario also uses actual production data but evaluates the plant's performance with an operational scenario where equipment undergoes maintenance and repairs, particularly those causing production losses. This scenario includes replacing damaged materials and labour costs for routine maintenance, such as solar panel cleaning.

The research method applies life cycle cost (LCC) and levelized cost of energy (LCOE) analysis, considering investment costs, operational costs, maintenance, and necessary replacements. This method is commonly used to determine a project's profitability at its inception.

This research aims to evaluate the solar power plant using a life cycle approach, considering the necessary maintenance costs over its lifespan to ensure the plant can produce as planned at the project's outset. Maintenance costs are calculated using the present value so they can be combined with the investment costs from 2016 and compared with the production over the plant's lifespan. The total costs over the lifespan are compared to the total output production to ensure that the chosen maintenance strategy is the most cost-effective for expenses and output production by calculating the levelized cost of energy (LCOE)

1.2. Theoretical Framework

In this research, several theories and concepts are fundamental in conceptualising the study of solar power plants in Indonesia, particularly within the context of a tropical climate and life cycle cost analysis.

1. **Tropical Climate and Solar Radiation**: The research draws on the concept of a tropical climate, where Indonesia's location on the equator influences the intensity of solar radiation received. Solar radiation intensity is a crucial factor in the efficiency of solar power plants. Although the radiation intensity at the research site only reaches 516 W/m², which is below the Standard Test Conditions (STC) of 1000 W/m², it is essential to understand how these conditions impact the performance of solar panels and energy production.
2. **Life Cycle Costing (LCC)**: The concept of Life Cycle Costing (LCC) is central to the economic analysis in this study. LCC is used to measure and manage the total costs associated with the construction and operation of a solar power plant over its lifespan. This includes initial investment costs, operational costs, maintenance costs, and component replacement costs. In the context of this research, LCC helps evaluate the

cost efficiency of different maintenance scenarios to maximise energy production at the lowest possible cost.

3. **Levelized Cost of Energy (LCOE)**: Another key concept is the Levelized Cost of Energy (LCOE), which measures the cost of energy production per unit over the lifetime of an energy project. LCOE takes into account all related costs, including investment, operation, maintenance, and replacements, and divides these by the total energy produced. In this study, LCOE is used to determine whether the maintenance strategies implemented are efficient and economical over the long term.
4. **Solar Module Degradation**: The theory of solar module degradation explains the decline in the performance of solar panels over time due to environmental and operational factors. This research considers degradation as a significant factor in projecting future energy production. Understanding the rate of degradation allows for more accurate predictions of future energy output and helps adjust the maintenance strategies needed to minimise its impact.
5. **Maintenance Management**: The concept of maintenance management is employed to evaluate various maintenance methods applied to solar power plants. In this study, different maintenance approaches are assessed based on their costs, including routine maintenance and the replacement of damaged components. The research explores how effective maintenance can minimise the decline in energy production and extend the lifespan of the equipment.

By integrating these theories and concepts, this research provides a comprehensive framework for analysing and optimising the performance of solar power plants in the tropical climate of Indonesia. It also sheds light on how costs and maintenance can be effectively managed to achieve maximum efficiency in energy production.

1.3. Conceptual Framework/Paradigm

In this study, the critical variables related to the performance of solar power plants in a tropical climate include:

1. Solar Radiation Intensity: This variable represents the amount of solar energy received per unit area, which directly impacts the efficiency and energy production of the solar power plants. In this research, solar radiation at the study site is lower than standard test conditions, significantly influencing the solar power plant’s performance.
2. Solar Module Degradation: This variable reflects the decline in the performance of solar panels over time due to environmental factors and wear and tear. Degradation affects the plant’s energy output and is critical to long-term performance projections.

3. Maintenance Methods: This variable encompasses the various strategies used to maintain the solar power plant. It includes routine maintenance (such as cleaning solar panels) and more intensive maintenance, such as replacing damaged components. The type and frequency of maintenance directly affect the solar power plant's operational efficiency and longevity.
4. Life Cycle Cost (L.C.C.): LCC is a variable that includes all costs associated with the solar power plant over its operational lifetime, including initial investment, maintenance, and component replacement costs. This variable is crucial for evaluating the plant's economic efficiency and identifying cost-effective maintenance strategies.
5. Levelized Cost of Energy (LCOE): LCOE measures the cost per unit of energy produced over the plant's lifespan. The rate of solar module degradation, maintenance costs, and the plant's production efficiency all impact it. This variable is essential for assessing the overall economic viability of the solar power plant.
6. The image below shows a block diagram or flowchart, indicating that energy production is influenced by the degradation of solar modules and the intensity of solar radiation. Maintenance activities can enhance the efficiency of solar power plants, positively impacting total energy production; however, maintenance activities have associated costs. Solar power electricity production results are calculated over the lifespan and compared with the costs during that period to determine whether the energy costs are optimal and in line with the initial project plan.

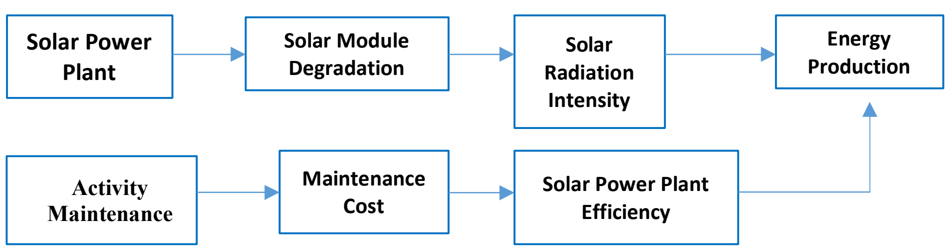

Figure 1. 1 Energy Production Solar Power Plant

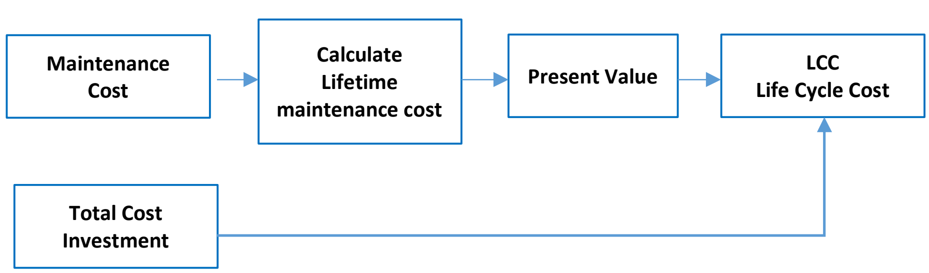

Figure 1. 2. Life Cycle Cost Method

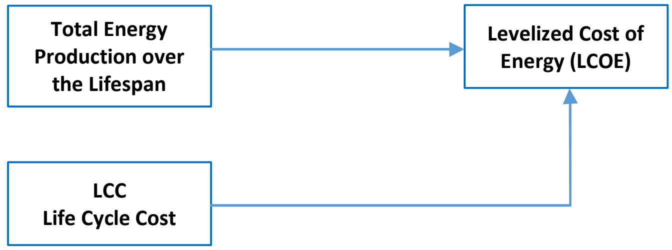

Figure 1. 3. Levelized Cost of Energy (LCOE)

1.4. Statement of the Problem

1. How does the production output or performance of a solar power plant fare after more than five years of operation, mainly when the plant is located in a tropical climate where sunlight intensity does not reach the Standard Testing Condition (S.T.C.) value or where the irradiation level is below 1000 W/m²? The solar power plant has operated in this case study for eight years.
2. What is the condition of the solar power plant if only routine maintenance (preventive maintenance) or "low maintenance" is performed? Is the health of the solar power equipment and the production of the solar power plant optimal, and what would be the optimal maintenance activities?
3. What are the impacts on equipment and electricity production under various maintenance scenarios for solar power plants? How is the average cost evaluation of electricity generated by solar power plants over their lifetime calculated based on LCOE? (Levelized Cost of Energy)

1.5. Research Objective

This research aims to conduct a comprehensive technical and economic assessment of solar power plants that have been operational for over five years in tropical regions, focussing on a case study of the plant located in Purwakarta, West Java, Indonesia. This solar power plant, built with a capacity of 1 MWp, has been in operation for eight years. The technical analysis will evaluate the plant's performance based on its energy production. Meanwhile, the economic analysis will assess the maintenance activities and associated costs, both current and future, required to ensure the plant operates as planned throughout its projection lifespan. The methodologies employed include life cycle cost (LCC) analysis and calculating the energy cost using the levelized cost of energy (LCOE) approach.

1.6. Hypothesis

1. The performance of solar power plants after operating for more than five years in a research location situated in a tropical climate, with solar intensity below Standard Testing Conditions (S.T.C.) or irradiation levels below 1000 W/m², will experience a decline in production due to the degradation of solar modules, which is expected to decrease by 20% over 25 years according to the solar module warranty.
2. The condition of solar power plants that only undergo routine maintenance (preventive maintenance) or "low maintenance" will experience potential equipment failures, resulting in a decline in production output performance or the plant's performance falling far below the initial project plan, with the potential that the solar power plant may not reach its 25-year lifespan.
3. An optimal maintenance scenario is needed so that solar power production can meet the initial production plan. For evaluation, a cost calculation is required over the lifespan, consisting of investment costs and maintenance costs, to be compared with the electricity generated over the lifespan or calculated based on LCOE. (Levelized Cost of Energy)
4. Optimal maintenance of solar power plants will result in optimal costs and a low LCOE (Levelized Cost of Energy).

1.7. Assumption

Solar Power Plants (PLTS) are considered low-maintenance systems, which means their operational and maintenance costs can be lower compared to other energy generation systems.

Solar Power Plants are regarded as low-maintenance because they generally do not have moving mechanical parts, meaning there is no risk of mechanical wear and tear that typically requires routine maintenance in other power systems, such as turbines or generators. Solar Power Plants have a long lifespan. Solar panels are designed to last 25 years or more, with relatively small efficiency losses each year, or a maximum of 20% over 25 years. This means that after the initial installation, maintenance requirements are very minimal. In general, solar power plants only require simple routine maintenance, such as cleaning the solar panels to ensure they are not covered with dust or dirt that could reduce efficiency. Additionally, periodic inspections of electrical connections and the condition of the inverter are necessary; however, these are relatively simple tasks. Other factors that contribute to solar power plants being considered low-maintenance systems include their low risk of damage because they are not exposed to extreme working conditions, such as high pressure or temperature, which could damage components. Furthermore, solar power plants do not require fuel like oil or coal, so there is no need for fuel management.

This research will prove that solar power plants require optimal preventive, corrective, and predictive maintenance rather than low-maintenance care. My research will compare three maintenance scenarios, one of which is low maintenance.

To evaluate energy costs, solar power generation costs over its lifespan will be compared. My research will assess an optimal maintenance scenario to demonstrate that the energy costs and maintenance expenses over the power plant's lifespan are the lowest when calculated using the Levelized Cost of Energy (LCOE).

1.8. Scope and Delimitation

1. The life cycle cost method is used to determine the most cost-effective maintenance expenses and production output over the lifespan of the solar power plant, aiming for the most optimal production results. Subsequently, an evaluation of energy costs or the levelized cost of energy (LCOE) is conducted.
2. Production data are compared using three scenarios based on the maintenance strategies employed. The production evaluation involves three scenarios. Scenarios 2 and 3 use actual data from the eight years of solar power plant operation, and these are compared with scenario 1, which represents the project's initial potential.
3. There are three maintenance scenarios:
    a. The first scenario involves evaluating the performance of the solar power plant (PLTS) using the initial potential when the PLTS was built and the initial project study data to estimate maintenance costs.
    b. The second scenario uses actual production data from the PLTS; however, the maintenance carried out is low maintenance, involving only preventive maintenance. In this scenario, no equipment replacement is performed, so there are no maintenance costs from material or component replacements when failures occur.
    c. The third scenario uses actual production data from the PLTS. It includes the maintenance and replacement of equipment that has failed, especially when the failure causes a decrease in PLTS production. The maintenance carried out in this scenario includes preventive, corrective, and predictive maintenance.
4. The limitations of this study are as follows:
    a. Equipment failures during operation were not analyzed using Root Cause Failure Analysis (RCFA).
    b. The impact of temperature on the performance of PV modules in solar power plants was not examined in this study. Solar power plant production data were