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Optimizing The Performance of Photovoltaic Power Plants Through the Root Cause Analysis Method

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ABSTRACT

Photovoltaic Power Plant (PV Power Plant) with various capacities, types, and locations have been built in Indonesia since 2011 until now, some of which have less than optimal performance and even do not last long. The limited management and problem-solving of PV Power Plant is the main obstacle. Several PV Power Plant performance analysis studies have been carried out but are still partial, not yet integrated from several aspects of the assessment. A thorough evaluation is needed by tracing the root causes of the problem in PV Power Plant, which is easy to understand and do in general on various types of PV Power Plant. In this study, an integrated PV Power Plant performance analysis was carried out through Root Cause Analysis and recommendations for follow-up solutions. The results of the research of PV Power Plant I (50 kWp, On-Grid), PV Power Plant II (100 kWp, Off-Grid), and PV Power Plant III (350 kWp, On-Grid), which are located on the islands of Sulawesi and Maluku show that the performance of PV Power Plant II and PV Power Plant III is not optimal (Performance Ratio < 60%) while PV Power Plant I is optimal. The results of the aggregation of the causes of the most significant losses come from Inverters, Batteries, and Solar Modules. The results of the Root Cause Analysis show that losses are caused by non-periodic maintenance factors, less reliable design and construction, low material quality, and inadequate PV Power Plant operator competence. Recommended priority for replacing damaged inverters and batteries includes optimizing design, material quality, construction, periodic maintenance, and regular training programs for operators. Based on the research results, the overall effort to optimize PV Power Plant performance through the Root Cause Analysis approach is easy to understand and easy to use in general for various types and capacities of PV Power Plant and different locations to optimize follow-up plans for improvements effectively for the sustainability of a PV Power Plant operation.

Keywords: PV Power Plant, Performance, Losses, Root Cause Analysis

I. INTRODUCTION

to Various things have been done to minimize the cost of electricity production, including supporting the Renewable Energy Program with a planned target of 23% in the Indonesian Energy Mix until 2024. Various Solar Power Plants (PV Power Plant) projects with various capacities and types have been built in Indonesia since 2011 until now. As of 2019, the PV Power Plant that has been operating has reached 70 MW consisting of 4 MW in Sumatra, 2 MW in Bali, 1 MW in Kalimantan, 31 MW in Sulawesi, 2 MW in Maluku, 28 MW in Nusa Tenggara and 2 MW in Papua [1]. In addition to great potential, PV Power Plant is an easy generator in the development process, but many PV Power Plant systems cannot last long due to component damage and low-performance Ratio (PR).

The location is spread out, and the capacity is relatively small, so PV Power Plant tends to be operated and managed by 1 Technician with limited expertise. This condition makes finding the cause of the problem in PV Power Plant more difficult. In addition, limited experience related to PV Power Plant technology, management methods, and problem-solving of PV Power Plant is also an obstacle. Therefore, the utilization of PV Power Plant is not optimal for the economic benefits, including investment costs.

Several PV Power Plant performance analysis studies have been carried out but are still partial, not yet integrated from several aspects of the assessment. A thorough evaluation is needed through tracing the root causes of the problem in PV Power Plant which is easy to understand and easy to do in general on various types of PV Power Plant. This research can complement previous studies, namely an integrated PV Power Plant performance analysis through Root Cause Analysis and recommendations for follow-up solutions.

The research was conducted by sampling 3 PV Power Plant Units in Indonesia consisting of different types and capacities and locations in the Archipelago area. The point is that the results of this research through an integrated root cause approach can be easily understood and carried out and can be used in general on various types and capacities of different PV Power Plant as an effort to optimize PV Power Plant performance effectively and support the sustainability of the PV Power Plant.

II. LITERATURE REVIEW

A. PV Power Plant Performance

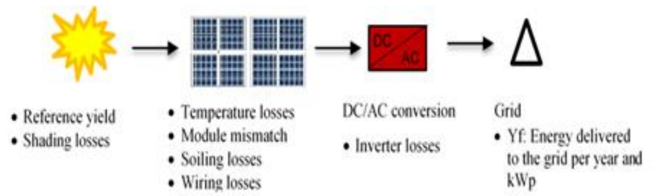

Figure 1: Overview of PV Power Plant Performance Evaluation

Figure 1 shows an overview of the PV Power Plant performance evaluation. Performance Ratio (PR) is a PV Power Plant performance parameter as in Table 1. A low PR value indicates high overall losses. A commonly used reference value is PR: 75% - 80% for PV Power Plant On-Grid and 65% for PV Power Plant Off Grid). Equation 1 provides a fast and simple way of estimating the energy production (Energy Yield) of PV Power Plant over a certain period.

$Y_f = PSH.W_{p\ PV}.PR$ ……………………….(1)

TABLE 1 PARAMETERS OF PV POWER PLANT PERFORMANCE

Parameter	Symbol	Unit
a. The final energy yield of the PV Power	Y_f	kWh/time (kWh/year)

Plant over a while (e.g. over one year)		
b. Peak Sun Hours incident on the PV Power Plant modules over the same period	PSH	(hours/year, PSH/year)
c. Peak nominal power of the PV Power Plant	Wp	kW_p
d. Performance Ratio of the PV Power Plant	PR	%, normally between 0.65 and 0.85

Source: PLN UPDL Makassar Learning Materials, 2014

In Equation 2, The Performance Ratio (PR) is calculated by comparing the actual energy produced during a certain period (Final Energy Yield, Yf) with the theoretically available energy calculated by the nominal output value of the PV Array (Reference Yield, Yr) and Peak Sun Hours available in that location.

$PR = \frac{Yf}{Yr}$.. (2)

In Equation 3, Yr is the theoretically available energy as it defines the solar radiation source for the PV system.

$Yr = H.A.\eta_{module}$.............................. (3)

Where: H: Irradiation for a certain time per year (kWh/m²); A: the active area of the module (m²); module: PV Module Efficiency (%)

Alternatively, Yr can be calculated by Peak Sun Hours (PSH) and the power value of the PV Array as in Equation 4.

$Yr = PSH.P_{peak}$................................ (4)

B. Root Cause Analysis (RCA)

RCA is a structured approach to identifying factors that influence one or more events so that they can be used to improve performance [31,32,33]. Several root cause analysis tools have been widely applied to identify root causes, namely 5Why Analysis, Fish Bone Diagram, and Root Cause Tree [34].

5Why Analysis is a simple root cause analysis tool that can be used to analyze system failures and can work well in identifying the causes and effects of an event. In addition, the use of RCA in the analysis of performance improvements can facilitate the tracking of factors that affect performance [35].

III. METHODS AND MATERIALS

A. Types and Scope of Research

The research was carried out on a sampling of 3 (three) PV Power Plant units with different types, capacities, and locations in Indonesia in the period January to May 2022, namely:

1. PV Power Plant I (S -05°22'32.60, E 119°49'46.30, Makassar, South Sulawesi, 50 kWp, On Grid Type),
2. PV Power Plant II (S -04°70'60.3, E 131°73'78.0, Masohi-Tioor Island, Maluku, 100 kWp, Off Grid Type),
3. PV Power Plant III (S 02°03'75.0, E 128°29'97.8, Wamama-Daruba Island, North Maluku, 350 kWp, On Grid Type).

This research is quantitative. The quantitative approach is used as follows:

1. Comparing the actual energy with the optimal output that should be from the PV Power Plant, where a Performance Ratio (PR) analysis is carried out which describes the PV Power Plant performance (optimal or not yet optimal).
2. Search the form of root cause analysis (Root Cause Analysis) to find the main causes of problems that affect the performance of PV Power Plant.
3. Aggregating the causes of PV Power Plant energy losses.
4. Develop an Action Plan to address the problems that have been analyzed previously.

5. Determine the priority scale recommendations for a follow-up to the Action Plan using the Cost-Benefit & Risk Analysis method through impact, cost, and risk assessments.

Figure 2 shows a conceptual model of research related to the optimization of PV Power Plant performance in an integrated manner through the Root Cause Analysis approach. The Economic and environmental analysis was not carried out in this research. Figure 3 shows research stage.

B. Data Collection and Data Processing Techniques

The data used in this study are as follows:

1. Primary data collection was carried out by collecting data on specifications and energy production for PV Power Plant On Grid 50 kWp Gowa-South Sulawesi, PV Power Plant Off Grid 100 kWp Tioor Island-Maluku, and PV Power Plant On Grid 350 kWp Wamama Island-North Maluku.
2. Secondary data collection and processing are carried out through the study of various references or literature including online calculation simulations through the Global Solar Atlas website and the use of the System Advisory Model (SAM) application.

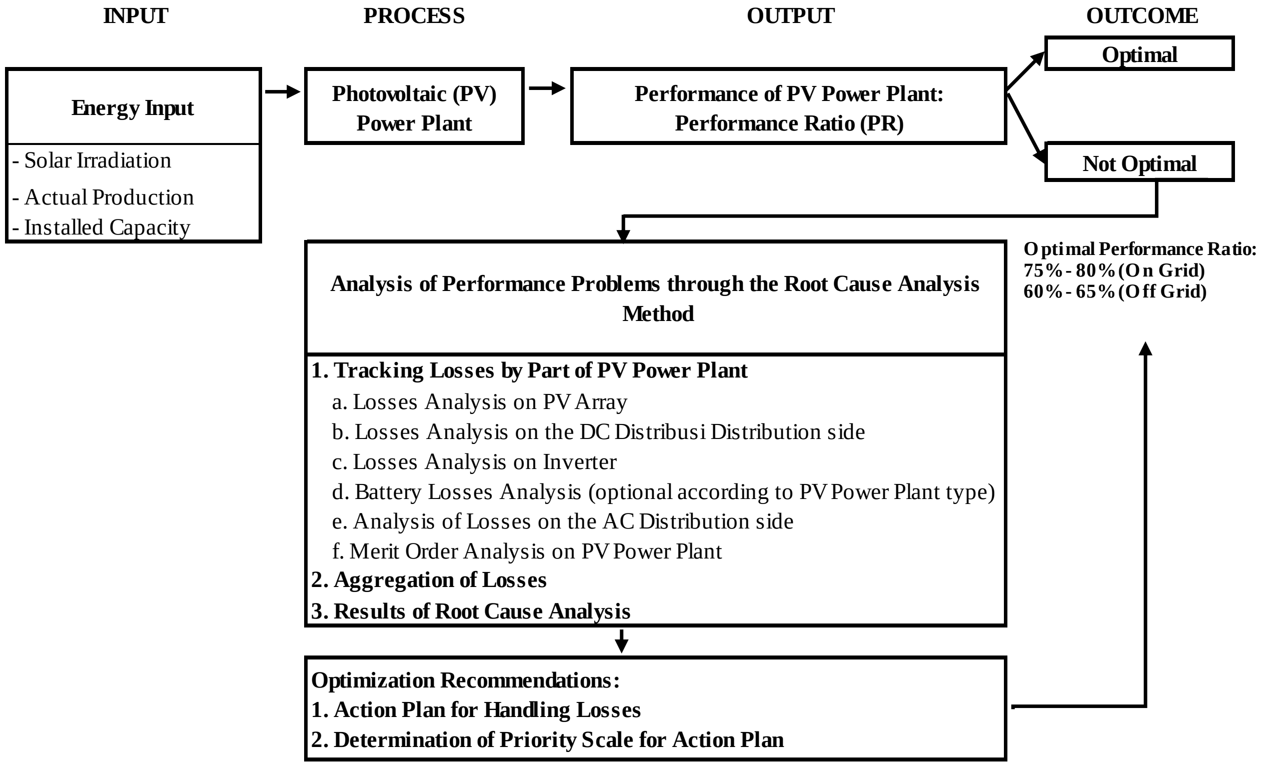

Figure 2. Conceptual Model of PV Power Plant Performance Optimization through Root Causes Analysis Method

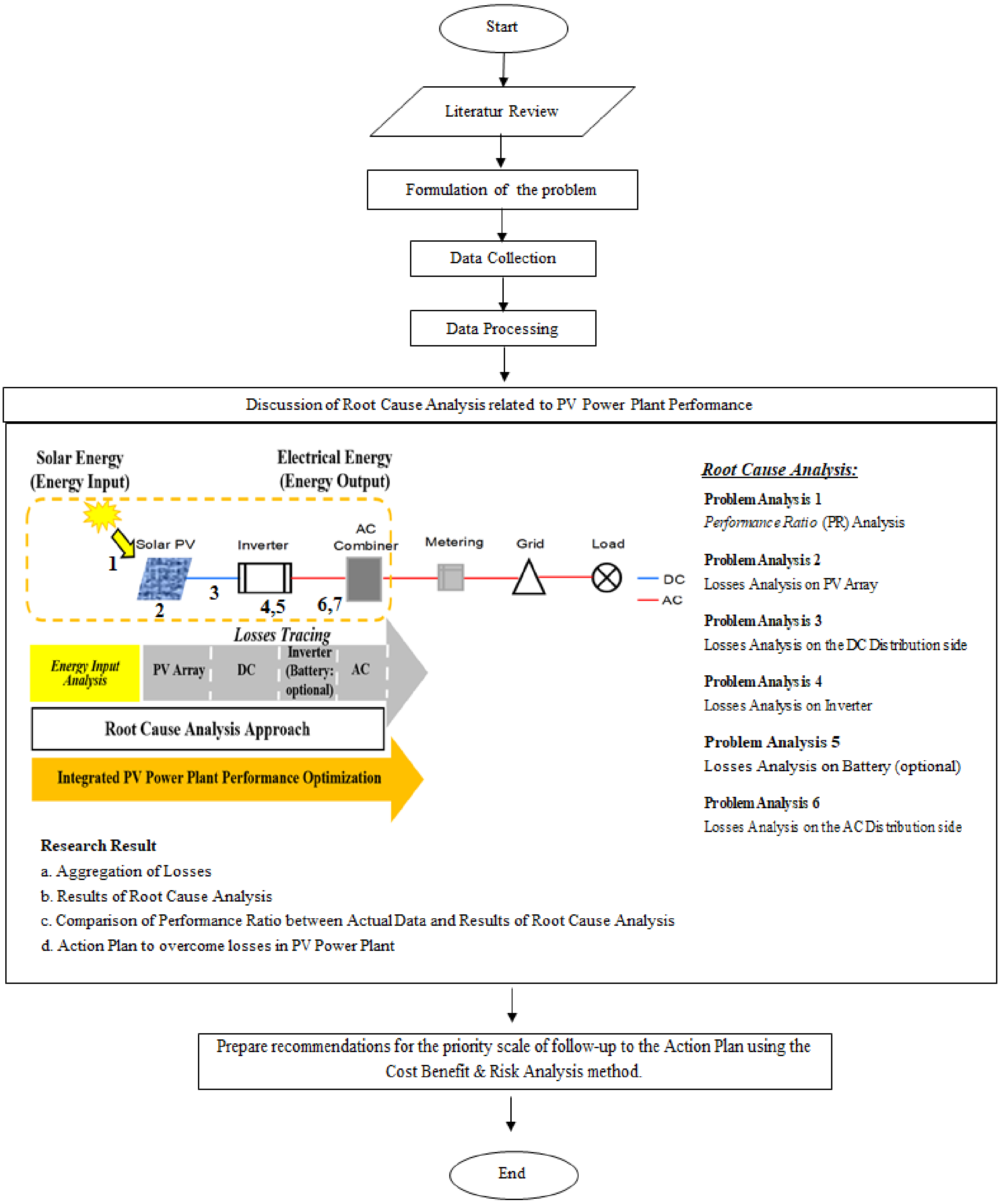

Figure 3 . Research Stages

IV. RESULTS AND DISCUSSION

A. Root Cause Analysis on The Performance of PV Power Plant I

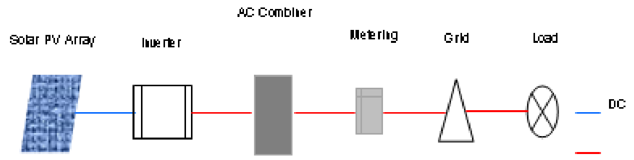

Figure 4. Single Line Diagram of PV Power Plant I

PV Power Plant I operates on an On-Grid basis (Figure 4), consisting of 160 Solar Modules, each with a capacity of 315 Wp. Each Array consists of 32 Solar Modules which are divided into 2 Strings where there are 16 Modules per String. The inverter in PV Power Plant I consists of 5 Grid Tie Inverter units with a capacity of 10 kW in each Array as in Table 2.

TABLE 2 SPESIFICATION OF PV POWER PLANT I

Data Description		**PV Power Plant I**
a.	Location	Gowa-Makassar, S -5°22'32.60, E 119°49'46.30
b.	Installed Capacity, Type, and Mounting	50 kWp, On-Grid, Fixed
c.	Solar Module:	
	Model, Technology, P0, Efficiency, Number of Units, Tilt Angle, Azimuth Angle	CS6X-315P, pc-Si, 315 Wp, 16,42 %, 160 Units, 18^0, 5^0
d.	Inverter	
	Model, P_{rated}, Efficiency, Number of Units	STP10000TL, 10 kW, 98%, 5 Units

The research was carried out through an analysis of the actual electrical energy production of PV Power Plant I on the potential production of electrical energy from PV Power Plant I. Furthermore, an online calculation simulation was carried out through the Global Solar Atlas website by entering PV Power Plant I specification data from Table 2. Based on the online calculation simulation through the Global Solar Atlas website, the potential for electrical energy production from PV Power Plant I is 203 kWh/day or 74.170 kWh/year as in Figure 5. The largest PV Power Plant I electrical energy production is in July, August, September, and October 2021 and peaks in August 2021.

Figure 5. Potential Electricity Production Simulation of PV Power Plant I

Source: https://globalsolaratlas.info/detail?c=-5.46727,123.240234,5&s=-5.22326,11949463&m=site&pv=ground,5,18,50 (access 3/8/2022)

According to Table 3, the Performance Ratio (PR) of PV Power Plant I in the 2017-2021 operating period is 3% - 89%. Where the lowest performance was in 2019 (PR: 3,72%) and the highest in 2021, namely PR at 89,92% with losses of 10,08%. Furthermore, the causes of these losses are further analyzed on the PV Array, DC side distribution, Inverter, and AC side distribution to determine the dominant cause that causes losses.

TABLE 3 PERFORMANCE DISCUSSION OF PV POWER PLANT I

Description		**PV Power Plant I (On Grid , 50 kWp, Makassar)**				
a	Electrical Energy Production (kWh)	2017	2018	2019	2020	2021
	Final Energy Yield (Y_f) (source: PV Power Plant I Actual Production)	33.870	9.148	2.762	20.553	66.691

	Reference Energy Yield (Y_r) (source: PV Power Plant I Production Potential)	74.170	74.170	74.170	74.170	74.170
b	Performance Ratio (PR)	45,67%	12,33%	3,72%	27,71%	89,92%
c	Losses	54,33%	87,67%	96,28%	72,29%	10,08%

Visually in Figure 6, the condition of the solar modules in PV Power Plant I is still good with routine maintenance carried out. Curve IV analysis cannot be done because of the availability of Special Tools IV Tester constraints. Based on the visual analysis of the module and IV curve, as well as the use of the System Advisory Model (SAM) application, the estimated losses in the PV Array are 8% (6.927 kWh) from the causes of shading (clouds, trees, buildings around), dust, and characteristics of the solar module.

Figure 6. Solar Module Condition of PV Power Plant I
Source: PLN UPDL Makassar, 11/23/2021

Figure 7 is done by observing the cables and equipment on the DC side, which is generally in normal conditions related to the DC connections and cables used so that the DC loss estimation uses a practical reference for DC losses and the use of the SAM application are 1% (989 kWh).

Figure 7. DC Distribution Side Condition of PV Power Plant I
Source: PLN UPDL Makassar, 11/23/2021

Visually in Figure 8, the condition of the inverter is normal so the efficiency of the inverter is the same as the nameplate specification, which is 98%. Inverter trips rarely occur so the operating envelope is safe (no problem). So that the estimation of losses on the Inverter uses a practical reference to losses on the Inverter and the use of the SAM application are 2% (2.542 kWh).

Figure 8. Inverter Condition of PV Power Plant I
Source: PLN UPDL Makassar, 11/23/2021

This is done by observing the cables and equipment on the AC side as in Figure 9, which is generally in normal conditions related to connections and cables on the AC side that are used. Thus, the estimation of losses on the AC side through practical references and the application of the SAM are 1 % (802 kWh).

Figure 9. AC Distribution Side Condition of PV Power Plant I | *Source: PLN UPDL Makassar, 11/23/2021*

Merit Order Analysis is 100% of PV production is absorbed by the system so that the estimated losses are below 1%. The Root Cause Analysis diagram of the causes of problems in the production of electrical energy in PV Power Plant I can be seen in Table 4.

Based on the analysis that has been done through the Root Cause Analysis method, the causes of losses in PV Power Plant I are aggregated as in Table 5.

TABLE 4 DIAGRAM OF ROOT CAUSE ANALYSIS RELATED TO ELECTRICAL ENERGY PRODUCTION LOSSES PV POWER PLANT I

Problem	Root Cause 1	Root Cause 2	Root Cause 3	Root Cause 4
LOSSES OF ELECTRICITY PRODUCTION ON PV POWER PLANT I: **HIGH (Losses: 12%, 13.801 kWh)**	Losses on PV Array	Shading of Trees	Non-routine maintenance	Monitoring and evaluation of maintenance have not been scheduled periodically.
		Shading of Buildings	Construction	PV Array Location Design
		Dust	Non-routine maintenance	Monitoring and evaluation of maintenance have not been scheduled periodically.
		Solar Module Efficiency	Solar Module Characteristics	Solar Module Design and Selection
	Losses on The DC Distribution Side	DC Cable	DC Cable Characteristics/Resistance	DC Cable Design and Selection
		DC Connection	DC Installation	DC Connection Check has not been scheduled periodically
	Losses on the Inverter	Inverter Efficiency	Inverter Characteristics	Inverter Design and Selection
	Losses on The AC Distribution Side	AC Cable	AC Cable Characteristics/Resistance	AC Cable Design and Selection
		AC connection	AC installation	AC Connection Check has not been scheduled periodically

TABLE 5 AGGREGATION ELECTRICAL ENERGY PRODUCTION LOSSES OF PV POWER PLANT I

No.	**Losses Group**	**Losses**	**Reason**	**Root Cause**
1.	Losses on PV Array	8%	Tree Shading	Monitoring and evaluation of maintenance have not been scheduled periodically.
			Building Shading	PV Array Design
			Dust	Monitoring and evaluation of maintenance have not been scheduled periodically.

			Solar Module Efficiency	Solar Module Design and Selection
2.	Losses on The DC Distribution Side	1%	DC Cable	DC Cable Design and Selection
			DC Connection	DC Connection Check has not been scheduled periodically
3.	Losses on the Inverter	2%	Inverter Efficiency	Inverter Design and Selection
4.	Losses on The AC Distribution Side	1%	AC Cable	AC Cable Design and Selection
			AC connection	AC Connection Check has not been scheduled periodically
5.	Losses from Merit Order	0%	-	-
TOTAL LOSSES		**12% (13.801 kWh)**		
PERFORMANCE RATIO(PR)		**88%**		

Based on the aggregation of losses from Table 5, the losses in PV Power Plant I are mostly caused by the PV Array group in the form of shading, dust, and characteristics of the Solar Module. In Table 6, the results of the comparison of Performance Ratio (PR) between Actual and Calculation (Root Cause Analysis approach) are presented.

TABLE 6 COMPARISON OF ACTUAL PR AND PR RESULTS OF ROOT CAUSE ANALYSIS IN PV POWER PLANT I

Actual Data	**Root Cause Analysis**	**Conclusion of the Root Cause Analysis Method**
PR: 89,92% (losses: 10,08%)	PR: 88% (losses: 12%)	Comparison of PR Actual Data & PR Root Cause Analysis is relatively appropriate, so that: a. The results of the Root Cause Analysis are close to the actual/reality in the field (PV Power Plant I site). b. The main root of the problem so that the production of electrical energy is not optimal by the energy potential of PV POWER PLANT 1: has been identified (dominantly caused by the PV Array group, namely the maintenance factor of shading & dust as well as the characteristics of the equipment on the solar module).

Furthermore, Table 7 is a recommendation on the priority scale of Action Plans to overcome PV Power Plant I performance problems through Cost-Benefit & Risk Analysis, namely analyzing the impact, costs, and risks of the Action Plan.

TABLE 7 ACTION PLAN PRIORITY SCALE RECOMMENDATIONS FOR PV POWER PLANT I

No.	Losses Group	Losses	Reason	Action Plan	Impact	Cost	Risk	Priority
1.	Losses on PV Array	8%	Tree Shading	Monthly periodic monitoring and evaluation, especially tree pruning	High	Low	Low	1
			Building Shading	Redesign and relocation of 1 PV Array affected by building shading	High	Low	Low	1
			Dust	Monthly periodic monitoring and evaluation, especially solar module cleaning	High	Low	Low	1
			Module Characteristics	When replacing the module better characteristics are selected	High	High	Low	2
2.	Losses on The DC Distribution Side	1%	Cable	When changing cables choose better characteristics	Low	Low	Low	2
			DC Connection	Quarterly DC Connection Check	High	Low	High	1
3.	Losses on The Inverter	2%	Inverter Characteristics	When replacing the Inverter better characteristics are selected	High	High	Low	2
4.	Losses on The AC Distribution Side	1%	Cable	When changing cables choose better characteristics	Low	Low	Low	2
			AC connection	Quarterly AC Connection Check	High	Low	Low	1

B. Root Cause Analysis on The Performance of PV Power Plant II

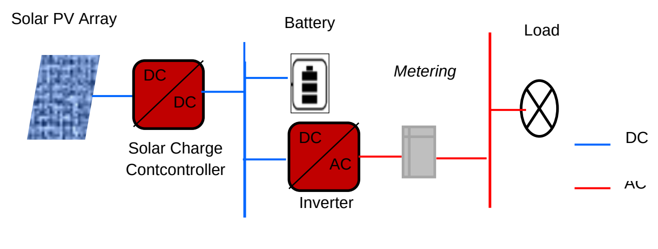

Figure 10. Single Line Diagram of PV Power Plant II

PV Power Plant II operates Off Grid as show in Figure 10, which consists of 560 Solar Modules with a capacity of 180 Wp each with a configuration consisting of 9 Arrays which are divided into 112 Strings, and each String is composed of 5 Solar Modules. The inverter in PV Power Plant II consists of 2 (two) Bi-Directional Inverter Units with a capacity of 60 kW per unit so that the total inverter capacity is 120 kW as in Table 8.

TABLE 8 SPECIFICATIONS OF PV POWER PLANT II

Data Description		PV Power Plant II
a.	Location	Tioor Island, Maluku, S -04°70'60.3, E 131°73'78.0.
b.	Installed Capacity, Type, and Mounting	100 kWp, Off Grid, Fixed
c.	Solar Module:	
	Model, Technology, P_0, Efficiency, Number of Units, Tilt Angle, Azimuth Angle	LEN 180 – 24M, mc-Si, 180 Wp, 14.50 %, 160 Units, 15^0, 0^0
d.	Inverter	
	Model, P_{rated}, Efficiency	MTP616F, 60 kW x 2 Units, 94%
e.	Battery	
	Model, Capacity, Nominal Voltage/cell, Number of Batteries	OpzS GFX – 2000, 2000 Ah, 2 V/ cell , 120 Pcs

The research was carried out through an analysis of the actual electrical energy production of PV Power Plant II on the potential production of electrical energy from PV Power Plant II. Furthermore, an online calculation simulation was carried out using the Global Solar Atlas website by entering PV Power Plant II specification data from Table 8. Based on an online calculation simulation through the Global Solar Atlas website as shown in Figure 11, the potential for electricity production from PV Power Plant II is 407 kWh/day or 148.728 kWh/year. The largest production of PV Power Plant II electrical energy is in August, September, October, and November 2021, and the peak is in August 2021.

Figure 11. Potential Electricity Production Simulation of PV Power Plant II

Source: https://globalsolaratlas.info/detail?c=-4.705775,131.738434,11&s=-4.70603,131.7378&m=site&pv=ground,0,6,100 (access 3/15/2022)

According to Table 9, the Performance Ratio (PR) in PV Power Plant II for the operating period 2018-2021 is around 9% - 16%. Where the highest PV Power Plant II performance in 2018 is PR at 16,30% and the lowest in 2021 (PR: 9,07%) with losses of 90,93%. Furthermore, further analysis of these losses is carried out on the PV Array, DC side distribution, battery, inverter, AC side distribution, and PV Power Plant II Merit Order to find out the dominant cause that causes losses.

TABLE 9 DISCUSSION ON THE PERFORMANCE OF PV POWER PLANT II

Performance Discussion		PV Power Plant II (Off Grid , 100 kWp, Tioor Island-Maluku)			
a.	Electrical Energy Production (kWh)	2018	2019	2020	2021
	Final Energy Yield (Y_f) (source: PV Power Plant II Actual Production)	12.350	24.430	20.890	16.710
	Reference Energy Yield (Y_r) (source: PV Power Plant II Production Potential)	148.728	148.728	148.728	148.728
b.	**Performance Ratio (PR)**	**16,30%**	**13,25%**	**11,33%**	**9,07%**
c.	**Losses**	**83,70%**	**86,75%**	**88,67%**	**90,93%**

Visually in Figure 12, the condition of the Solar Modules in PV Power Plant II has degraded due to dust crust on the edges of the solar module. In addition, shading constraints also cause disturbances in the production of PV Power Plant II electrical energy. Curve IV analysis cannot be carried out due to constraints on the availability of Special Tools IV Testers. Based on the visual analysis of the module and the use of the System Advisory Model (SAM) application, the estimated losses in the PV Array PV Power Plant II are 12% (17.847 kWh).

Figure 12. Solar Module Condition of PV Power Plant II

Source: PLN UIW Maluku, 3/2/2022

Figure 13 show tracing cables and equipment on the DC side, where there are problems with some loose connection points, so the DC losses estimation uses a practical reference for DC losses and the use of the System Advisory Model (SAM) application are 2% (2.977 kWh).

Figure 13. DC Distribution Side Condition of PV Power Plant II

Source: PLN UIW Maluku, 3/2/2022

Inverter efficiency is the same as the nameplate specification which is 94% (6% loss). Based on the search as in Figure 14, only 1 Unit Bi-directional Inverter can operate out of a total of 2 Units, whereas 1 Unit Bi-directional Inverter has been in an off condition due to damage until now. Inverter trips often occur so that there is a problem with the operating envelope and it takes time for further inspection.

Figure 14. Inverter Condition of PV Power Plant II

Source: PLN UIW Maluku, 3/2/2022

The problems with the PV Power Plant II inverter caused the PV Power Plant II electricity production to be significantly low. With the condition that 1 unit is damaged and the inverter efficiency is 94% and with the use of the System Advisory Model (SAM) application, the estimated losses on the PV Power Plant II inverter is 56% (83.287 kWh). From an interview with the PV Power Plant Manager, information was obtained regarding the main challenge, namely the operator who has limited competence in the form of knowledge and skills in operating and maintaining inverters.

Physical analysis in Figure 15, which is to analyze the condition of the battery physically. Based on the investigation, most of the batteries have been sulfated (sulfate buildup) and are damaged. Based on these conditions and the use of the System Advisory Model (SAM) application, the estimated losses in the PV Power Plant II battery are 20% (29.745 kWh).

Figure 15. Battery Condition of PV Power Plant II
Source: PLN UIW Maluku, 3/2/2022

Based on an interview with the PV Power Plant Manager, information was obtained regarding the main obstacle, namely the operator who has limited competence in the form of knowledge and skills in operating and maintaining batteries.

Figure 16 is done by tracing the cables and equipment on the AC side, which is generally in normal conditions regarding the connections and cables on the AC side that are used. Estimated losses on the AC side through practical references and the application of the System Advisory Model (SAM) is 2 % (2.974 kWh). Merit Order Analysis is 100% of PV production is absorbed by the system so that the estimated losses are below 1%.

Figure 16. AC Distribution Side Condition of PV Power Plant II
Source: PLN UIW Maluku, 3/2/2022

Thus, a comprehensive Root Cause Analysis of the causes of problems in the production of electrical energy in PV Power Plant II can be presented in Table 10.

TABLE 10 DIAGRAM OF ROOT CAUSE ANALYSIS RELATED TO ELECTRICAL ENERGY PRODUCTION LOSSES PV POWER PLANT II

Problem	Root Cause 1	Root Cause 2	Root Cause 3	Root Cause 4
LOSSES OF ELECTRICITY PRODUCTION ON PV POWER PLANT II:	Losses on PV Array	Module Degradation from Dust Crust	Non-routine maintenance	Monitoring and Evaluation of Module Maintenance has not been scheduled periodically
		Shading of Trees	Non-routine maintenance	Monitoring and Evaluation of Module Maintenance has not been scheduled periodically
		Solar Module Efficiency	Solar Module Characteristics	Solar Module Design and Selection
VERY	Losses on	DC Cable	DC Cable	DC Cable Design and Selection

HIGH (Losses: 92%, 132.018 kWh)	The DC Distribution Side		Characteristics	
		DC Connection	DC Installation	DC Connection Check has not been scheduled periodically
	Losses on The Inverter	Inverter trips frequently & 1 Unit is broken	Inverter Maintenance	Operator competency related to inverter operation and maintenance is lacking
		Inverter Efficiency	Inverter Characteristics	Inverter Design and Selection
	Losses on Battery	Sulfation in Batteries	Battery Check	Monitoring and Evaluation of Battery Maintenance has not been scheduled periodically
		Broken battery	Battery Operation and Maintenance	Operator competency related to battery operation and maintenance is lacking
		Battery Efficiency	Battery Characteristics	Battery Design and Selection
	Losses on The AC Distribution Side	AC Cable	AC Cable Characteristics	AC Cable Design and Selection
		AC connection	AC installation	AC Connection Check has not been scheduled periodically

Based on the analysis that has been done through the Root Cause Analysis method, the causes of losses in PV Power Plant II are grouped (aggregated) as in Table 11. Based on Table 11, the dominant cause of losses in PV Power Plant II is caused by the inverter group in the form of inverter damage and inverter characteristics. Furthermore, the results of the comparison of Performance Ratio (PR) between Actual Data and Calculations (Root Cause Analysis approach) are relatively appropriate as in Table 12.

TABLE 11 AGGREGATION ELECTRICAL ENERGY PRODUCTION LOSSES OF PV POWER PLANT II

No.	**Losses Group**	**Losses**	**Reason**	**Root Cause**
1.	Losses on PV Array	12%	Dust Crust	Monitoring and Evaluation of Module Maintenance has not been scheduled periodically
			Tree Shading	Monitoring and Evaluation Periodic maintenance of unscheduled trees
			Solar Module Efficiency	Solar Module Design and Selection
2.	Losses on The DC Distribution Side	2%	DC Cable	DC Cable Design and Selection
			DC Connection	Periodic unscheduled DC Connection Check
3.	Losses on The Inverter	56%	Inverter trips frequently & 1 Unit is broken	Operator competency related to inverter operation and maintenance is lacking

			Inverter Efficiency	Inverter Design and Selection
4.	Losses on Battery	20%	Sulfation in Batteries	Monitoring and Evaluation of Battery Maintenance has not been scheduled periodically
			Broken battery	Operator competency related to battery operation and maintenance is lacking
			Battery Efficiency	Battery Design and Selection
5.	Losses on The AC Distribution Side	2%	AC Cable	AC Cable Design and Selection
			AC connection	Periodic unscheduled AC connection checks
6.	Losses from Merit Order	0%	-	-
TOTAL LOSSES		**92% (132.018 kWh)**		
PERFORMANCE RATIO (PR)		**8%**		

TABLE 12 COMPARISON OF ACTUAL PR AND PR RESULTS OF ROOT CAUSE ANALYSIS IN PV POWER PLANT II

Actual Data	**Root Cause Analysis**	**Conclusion of the Root Cause Analysis Method**
PR: 9,07% (losses: 90,93%)	PR: 8% (loss : 92%)	Comparison of PR Actual Data & PR Root Cause Analysis is relatively appropriate, so that: a. The results of the Root Cause Analysis are close to the actual/reality in the field (PV Power Plant II site). b. The main root cause of the very low production of electrical energy in PV Power Plant II has been identified (a significant cause for the Inverter & Battery group).

In Table 13, recommendations for the priority scale of the Action Plan are presented to overcome PV Power Plant II performance problems determined through Cost-Benefit & Risk Analysis, namely analyzing the impact, costs, and risks of the Action Plan.

TABLE 13 ACTION PLAN PRIORITY SCALE RECOMMENDATIONS FOR PV POWER PLANT II

No.	**Losses Group**	**Losses**	**Reason**	**Action Plan**	**Impact**	**Cost**	**Risk**	**Priority**
1.	Losses on PV Array	12%	Dust Crust	Monthly periodic monitoring and evaluation, especially solar module cleaning	High	Low	Low	1
			Tree Shading	Monitoring and Evaluation Monthly periodic maintenance, especially tree pruning	High	Low	Low	1
			Solar	When replacing the module	High	High	Low	2

			Module Efficiency	better characteristics are selected				
2.	Losses on The DC Distribution Side	2%	DC Cable	When changing cables choose better characteristics	Low	High	Low	2
			DC Connection	Quarterly DC Connection Check	High	Low	High	1
3.	Losses on the Inverter	56%	Inverter trips frequently & 1 Unit is broken	Replace the broken inverter and check the inverter regularly	High	High	High	1
				Periodic training for Operators regarding Inverter Operation and Maintenance	High	Low	Low	1
			Inverter Efficiency	When replacing the entire inverter, better characteristics are selected	High	High	Low	2
4.	Losses on Battery	20%	Sulfation in Batteries	Battery Replacement	High	High	High	1
				Regular cleaning and battery checks per month	High	Low	Low	1
			Broken battery	Battery Replacement	High	High	High	1
				Periodic training for Operators regarding Battery Operation and Maintenance	High	Low	Low	1
			Battery Efficiency	When replacing the entire battery, better characteristics are selected	High	High	Low	2
5.	Losses on The AC Distribution Side	2%	AC Cable	When replacing the entire AC cord, better characteristics are selected	Low	High	Low	2
			AC connection	Quarterly AC Connection Check	High	Low	Low	1

C. Root Cause Analysis on The Performance of PV Power Plant III

PV Power Plant III operates On-Grid as in Figure 17, consisting of 1.348 Solar Modules with a capacity of 260 Wp each with a configuration consisting of 56 Arrays which are divided into 164 Strings and each String contains 8 Solar Modules and 4 Strings consisting of 9 Modules per String. The inverter in PV Power Plant III consists of 14 Grid Tie Inverter Units with a capacity of 25 kW in each Array as in Table 14.

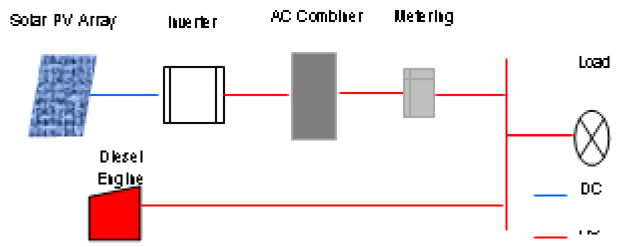

Figure 17. Single Line Diagram of PV Power Plant III

TABLE 14 SPECIFICATIONS OF PV POWER PLANT III

Data Description		PV Power Plant III
a.	Location	Wamama-Daruba, North Maluku , S 02°03'75.0, E 128°29'97.8
b.	Installed Capacity, Type, and Mounting	350 kWp, On-Grid, Fixed
c.	Solar Module:	
	Model, Technology, P_0, Efficiency, Number of Units	LEN 260 Wp , mc-Si, 260 Wp , 16%, 1,348 Units
	Tilt Angle, Azimuth Angle	3^0 , 180^0
d.	Inverter	
	Model, P_{rated}, Efficiency, Number of Units	STP25000TL-30, 25 kW , 98%, 14

The research was carried out through an analysis of the actual electrical energy production of PV Power Plant III on the potential for production of electrical energy from PV Power Plant III. Furthermore, an online calculation simulation was carried out using the Global Solar Atlas by entering PV Power Plant III specification data from Table 14.

Figure 18. Potential Electricity Production Simulation Of PV Power Plant III

Source:

https://globalsolaratlas.info/detail?c=2.087627,128.301086,11&s=2.0375,128.29978&m=site&pv=ground,3,180,350 (access 3/8/2022)

Based on the online calculation simulation through the Global Solar Atlas website as presented in Figure 18, information on the potential for electrical energy production from PV Power Plant III is 1.516 kWh/day or 553.247 kWh/year. Based on Figure 18, the largest electrical energy production is in March, April, May, August, September, and October 2021 and peaks in October 2021. From the actual electrical energy production data and online calculation simulations related to the electrical energy potential of PV Power Plant III (according to Figure 18), Table 15 is the result of the analysis of PV Power Plant III performance.

TABLE 15 DISCUSSION ON THE PERFORMANCE OF PV POWER PLANT III

Research Description		PV Power Plant III (On Grid , 350 kWp, Wamama Island-North Maluku)			
a.	Electrical Energy Production (kWh)	2018	2019	2020	2021

	Final Energy Yield (Y_f) (source: PV Power Plant III Actual Production)	258.729	234.151	186.447	29.228
	Reference Energy Yield (Y_r) (source: PV Power Plant III Production Potential)	553.247	553.247	553.247	553.247
b.	**Performance Ratio (PR)**	**37,57%**	**34,01%**	**27,08%**	**14,86%**
c.	**Losses**	**62,43%**	**65,99%**	**72,92%**	**85,14%**

Based on Table 15, the evaluation of the PV Power Plant III Performance Ratio (PR) in the 2018-2021 operating period is around 14% - 37%. Where the highest PV performance in 2018 is PR at 37,57% and will decrease until 2021 (PR: 14,86%) with losses increasing to 85,14% in 2021. Furthermore, these losses are analyzed further on PV Array, DC side distribution, Inverter, AC side distribution, and Merit Order PV Power Plant III to find out the dominant cause that causes losses.

Visually in Figure 19, the condition of the PV Power Plant III solar module is that most of the problems are caused by unreliable construction, unequal module types, rust on the edges of the module, a lot of dust on the module, and the impact of shading from the surrounding environment (grass) height, trees, buildings, between modules which causes large losses in the PV Array. Curve IV analysis cannot be done because of the availability of Special Tools IV Tester constraints. Based on the visual analysis of the module and the use of the System Advisory Model (SAM) application, the estimated losses in the PV Array PV Power Plant III are 45 % (248.961 kWh).

Figure 19. Solar Module Condition of PV Power Plant III

Source: PLN UIW Maluku, 3/4/2022

Figure 20 is done by tracing the cables and equipment on the DC side, where there are problems with some loose connection points so that the DC losses estimation uses a practical reference for DC losses and the use of the System Advisory Model (SAM) application of 10% (55.325 kWh).

Figure 20. DC Distribution Side Condition of PV Power Plant III

Source: PLN UIW Maluku, 3/4/2022

Physically the condition of some inverters is not normal, causing quite high losses on the inverters as ini Figure 21. Inverter trips often occur so that there is a problem with the operating envelope and it takes time for further inspection. The problems in the PV Power Plant III inverter caused the PV Power Plant III electricity production to be significantly low. With these conditions and through the use of the System Advisory Model (SAM) application, the estimated losses in the PV Power Plant III Inverter are 30% (165.974 kWh).

Figure 21. PV Power Plant III Inverter Condition

Source: PLN UIW Maluku, 3/4/2022

Based on an interview with the PV Power Plant Manager, information was obtained regarding the main obstacle, namely the operator who has limited competence in the form of knowledge and skills in operating and maintaining inverters.

Figure 22 is done by tracing the cables and equipment on the AC side, which is generally in normal conditions related to connections and cables on the AC side that are used. Thus, the estimation of losses on the AC side through practical references and the application of the System Advisory Model (SAM) is 2 % (11.065 kWh).

Figure 22. AC Distribution Side Condition of PV Power Plant 3

Source: PLN UIW Maluku, 3/4/2022

Merit Order Analysi is 100% of PV production is absorbed by the system so that the estimated losses are below 1%. Thus, the overall Root Cause Analysis of the causes of problems in the production of electrical energy in PV Power Plant III can be shown in Table 16.

Based on the analysis that has been done through the Root Cause Analysis method, the causes of losses in PV Power Plant III can be aggregated according to Table 17.

TABLE 16 DIAGRAM OF ROOT CAUSE ANALYSIS RELATED TO ELECTRICAL ENERGY PRODUCTION LOSSES PV POWER PLANT III

Problem	Root Cause 1	Root Cause 2	Root Cause 3	Root Cause 4
PV POWER PLANT 3 ELECTRICITY PRODUCTION LOSSES: VERY HIGH (Losses: 87%, 524.019 kWh)	Losses on PV Array	Less reliable construction	PV Array design and installation are not suitable	Less Module Installation Check and Evaluation
		Module type is not the same	Module procurement is not according to the design	Less Module Installation Check and Evaluation
		Module Degradation from Rusty Crust	Irregular maintenance and low material quality	Monitoring and Evaluation of Module Maintenance has not been scheduled periodically
		Dust	Non-routine maintenance	Monitoring and Evaluation of Module Maintenance has not been

				scheduled periodically
		Shading of tall grass	Non-routine maintenance	Monitoring and Evaluation The maintenance of the surrounding environment has not been scheduled periodically
		Shading of Trees	Non-routine maintenance	Monitoring and Evaluation Periodic maintenance of unscheduled trees
		Shading of the surrounding buildings	Construction	PV Array location design
		Shading between modules	PV Array installation is not according to the design	Insufficient installation check and evaluation
		Solar Module Efficiency	Solar Module Characteristics	Solar Module Design and Selection
	Losses on The DC Distribution Side	DC Cable	DC Cable Characteristics/Resistance	DC Cable Design and Selection
		DC Connection	DC Installation	DC Connection Check has not been scheduled periodically
	Losses on the Inverter	Inverter trips frequently	Inverter operation interruption, Inverter Maintenance	Operator competency related to inverter operation and maintenance is lacking
		Inverter Efficiency	Inverter Characteristics	Inverter Design and Selection
	Losses on The AC Distribution Side	AC Cable	AC Cable Characteristics/Resistance	AC Cable Design and Selection
		AC connection	AC installation	AC Connection Check has not been scheduled periodically

TABLE 17 AGGREGATION LOSSES OF ELECTRICAL ENERGY PRODUCTION ON PV POWER PLANT 3

No.	Losses Group	Losses	Reason	Root Cause
1.	Losses on PV Array	45%	Less reliable construction	Less Module Installation Check and Evaluation
			Module type is not the same	Less Module Installation Check and Evaluation
			Module Degradation from Rusty Crust	Monitoring and Evaluation Maintenance of periodic unscheduled modules
			Dust	Monitoring and Evaluation of Module Maintenance has not been scheduled periodically
			Tall grass shading	Monitoring and Evaluation The maintenance of the surrounding environment has not been scheduled periodically
			tree shading	Monitoring and Evaluation Periodic maintenance of unscheduled trees
			Shading of surrounding buildings	PV Array location design
			Shading between modules	Insufficient installation check and evaluation
			Solar Module Efficiency	Solar Module Design and Selection
2.	Losses on The DC Distribution Side	10%	DC Cable	DC Cable Design and Selection
			DC Connection	DC Connection Check has not been scheduled periodically
3.	Losses on the Inverter	30%	Inverter trips frequently	Inverter Operation Interruption
				Operator competency related to inverter operation and maintenance is lacking
			Inverter Efficiency	Inverter Design and Selection
4.	Losses on The AC Distribution Side	2%	AC Cable	AC Cable Design and Selection
			AC connection	AC Connection Check has not been scheduled periodically
5.	Losses from Merit Order	0%	-	-
TOTAL LOSSES		**87% (524.019 kWh)**		
PERFORMANCE RATIO (PR)		**13%**		

According to Table 17, the dominant cause of losses in PV Power Plant III is from the PV Array group and the Inverter group. Furthermore, the results of the comparison of Performance Ratio (PR) between Actual Data and Calculation (Root Cause Analysis approach) in PV Power Plant 3 are relatively appropriate as in Table 18.

TABLE 18 COMPARISON OF ACTUAL PR AND PR RESULTS OF ROOT CAUSE ANALYSIS IN PV POWER PLANT III

Actual Data	Root Cause Analysis	Conclusion Root Cause Analysis Method
PR: 14,86 % (losses: 85,14%)	PR: 13% (losses: 87%)	Comparison of PR Actual Data & PR Root Cause Analysis is relatively appropriate, so that: a. The results of the Root Cause Analysis are close to the actual/reality in the field (PV Power Plant III site). b. The main root cause of very low electrical energy production in PV Power Plant III successfully identified (a significant cause of the PV Array group)

Recommendations for the priority scale of the Action Plan are presented to overcome PV Power Plant III performance problems determined through Cost-Benefit & Risk Analysis, namely analyzing the impact, costs, and risks of the Action Plan as in Table 19.

TABLE 19 ACTION PLAN PRIORITY SCALE RECOMMENDATIONS FOR PV POWER PLANT III

No.	Losses Group	Losses	Reason	Action Plan	Impact	Cost	Risk	Priority
1.	Losses on PV Array	45%	Less reliable construction	Reinforcement of PV Array Construction by Design	Low	Low	High	2
			Module type is not the same	Module Installation according to the same Design and Specification	High	Low	Low	1
			Module Degradation from Rusty Crust	Replacement of rusty crust module	High	Low	Low	1
				Monitoring and Evaluation Periodic maintenance per month, especially the risk of scale rust	High	Low	Low	1
			Dust	Monthly periodic monitoring and evaluation, especially solar module cleaning	High	Low	Low	1
			Tall grass shading	Monthly periodic monitoring and evaluation, especially	High	Low	Low	1

				cleaning of Plants around the PV Array				
			tree shading	Monitoring and Evaluation Monthly periodic maintenance, especially tree pruning	High	Low	Low	1
			Shading of surrounding buildings	Redesign and relocation of PV Arrays affected by building shading	High	Low	Low	1
			Shading between modules	Reinforcement of PV Array Construction by Design	High	Low	Low	1
			Solar Module Efficiency	When replacing the entire module, better characteristics are selected	High	High	Low	2
2.	Losses on The DC Distribution Side	10%	DC Cable	When changing cables choose better characteristics	Low	High	Low	2
			DC Connection	Periodic unscheduled DC Connection Check	High	Low	Low	1
3.	Losses on the Inverter	30%	Frequent inverter trip	Replace the broken inverter and check the inverter regularly	High	Low	High	1
				Periodic training for Operators regarding Inverter Operation and Maintenance	High	Low	Low	1
			Inverter Efficiency	Inverter Design and Selection	High	High	Low	1
4.	Losses on The AC Distribution Side	2%	AC Cable	When changing cables choose better characteristics	Low	Low	Low	2
			AC connection	Quarterly AC Connection Check	Low	Low	Low	2

D. Executive Summary of Research

Based on the discussion of Root Cause Analysis in PV Power Plant I, PV Power Plant II, and PV Power Plant III, the following presents a summary of the research that has been carried out as in Table 20.

TABLE 20. EXECUTIVE SUMMARY OF RESEARCH

Case Study		PV Power Plant I	PV Power Plant II	PV Power Plant III
A.	**Research Data**			
a.	Location	Gowa-Makassar, South Sulawesi	Tioor Island, Maluku	Wamama Island, Daruba Island, North Maluku

b.	Installed capacity	50 kWp (PLN asset)	100 kWp (PLN asset)	350 kWp (Government asset)
c.	Type, Mounting	On-Grid, Fixed	Off Grid, Fixed	On-Grid, Fixed
d.	Solar Module:			
	Models, Technology	CS6X-315P, pc-Si	LEN 180 – 24M, mc-Si	LEN 260 Wp, mc-Si
	P_0, Efficiency	315 Wp, 16.42%	180 Wp, 14.50%	260 Wp, 16.00 %
	Number of Units, Tilt Angle, Azimuth Angle	160 Units, 18 ^{0}, 5 ^{0}	560 Units, 15 ^{0}, 0 ^{0}	1348 Units, 3 ^{0}, 180 ^{0}
e.	Inverter			
	Model	STP10000TL	MTP616F	STP25000TL-30
	P_{rated}, Efficiency, Number of Units	10 kW, 98%, 5	60 kW, 94%, 2	25 kW, 98%, 14
f.	Operation Time	2017 to now	2018 to now	2018 to now
g.	Monitoring Period	5 years	4 years	4 years
Case Study		**PV Power Plant I**	**PV Power Plant II**	**PV Power Plant III**
h.	Energy Yield (kWh) Actual	2021	2021	2021
	Final Energy Yield (Yf)	66.691	16.710	29.228
B.	**Research Result**			
	Reference Energy Yield (Y_r) (PV Power Plant Electrical Energy Potential)	74.170 kWh/Year	148.728 kWh/Year	553.247 kWh/Year
i.	Performance Ratio (PR)	88%	8%	13%
j.	**Losses Aggregation** Losses on PV Array Losses on The DC Distribution Side Losses on the Inverter Losses on The AC Distribution Side Losses on Battery	**12% (7.479 kWh)** 8% (6.927 kWh) 1% (989 kWh) 2% (2.542 kWh) 1% (802 kWh)	**92% (132.018 kWh)** 12% (17.847 kWh) 2% (2.977 kWh) 56% (83.287 kWh) 2% (2.974 kWh) 20% (29.745 kWh)	**87% (524.019 kWh)** 45% (248.961 kWh) 10% (55.325 kWh) 30% (165.974 kWh) 2% (11.065 kWh)
k.	Causes of Losses	a. Shading (trees, buildings) b. Module Degradation from Dust Scale	a. Degradation from Dust Scale b. Shading (tree) c. Sulfation in Batteries d. Battery and Inverter damaged	a. Module Degradation from Rusty Crust b. Shading (grass, trees) c. Inverter is broken d. Frequent inverter trip
l.	Root Cause Analysis Causes of Losses	a. Improper design and	a. Monitoring and Evaluation of Module	a. Maintenanc e is not routine and

		construction b. Monitoring and Evaluation Maintenance of periodic unscheduled modules	Maintenance have not been scheduled periodically. b. Monitoring and Evaluation of tree maintenance have not been scheduled periodically c. Monitoring and Evaluation of Battery Maintenance have not been scheduled periodically. d. Operator competence regarding the operation and maintenance of Batteries and Inverters are inadequate	the quality of the material is low. b. Monitoring and Evaluation The maintenance of the surrounding environment has not been scheduled periodically. c. Inverter operation interruption. d. Operator competency related to inverter operation and maintenance is inadequate.
m.	Action Plan Priority Scale Recommendations for Optimizing PV Power Plant Performance	a. Relocation of PV Array affected by building shading b. Regular maintenance of dust and trees	a. Monthly monitoring and evaluation, especially the cleaning of the Solar Module. b. Monitoring and Evaluation Monthly periodic maintenance, especially tree pruning c. Damaged Inverter and Battery Replacement. d. Periodic training for Operators regarding Operation and Maintenance of Inverters and Batteries.	a. Replacement of damaged solar modules of the same type b. Monthly periodic monitoring and evaluation, especially cleaning of Plants around the PV Array c. Broken Inverter Replacement d. Periodic training for Operators regarding Inverter Operation and Maintenance

V. CONCLUSION

1. Design, material quality, construction, and periodic maintenance greatly determine the performance of PV Power Plant.
2. Information System Technology in PV Power Plant is very important and needed for the effectiveness of monitoring and evaluating PV Power Plant performance in real-time.

3. Efforts to optimize PV Power Plant performance as a whole through a root cause analysis approach are easy to understand and easy to use in general for various types and capacities of PV Power Plant as well as different locations.
4. Root Cause Analysis method can effective and efficient to optimize follow-up plans to improve PV Power Plant performance and supports the sustainability of the operation of a PV Power Plant.

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