FICHTNER

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PV Plant Operational Survey

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Promotion of Renewable Energies - Phase VII (GAF - RE)

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Abbreviations

Abbreviation	Explanation
AC	Alternating Current
AMD	Armenian Dram
BESS	Battery Energy Storage Systems
COD	Commercial Operation Date
CSR	Corporate Social Responsibility
DAQ	Data Acquisition
DC	Direct Current
ENA	Electric Networks Armenia
EPC	Engineering, Procurement, Construction
EYA	Energy Yield Assessment
GHI	Global Horizontal Irradiation
GII	Global Inclined Irradiance
HDG	Hot-Dip Galvanized
HMI	Human Machine Interface
HSE	Health, Safety & Environment
HV	High Voltage
IEC	International Electrotechnical Commission
kW	Kilowatt
LTSA	Long Term Service Agreement
MV	Medium Voltage
MVA	Megavolt-ampere
O&M	Operation and Maintenance
OE	Owner's Engineer
OEM	Original Equipment Manufacturer
OHTL	Overhead Transmission Line
PM	Particulate Matter

Abbreviation	Explanation
PSRC	Public Services Regulatory Commission
PV	Photovoltaic
RE	Renewable
SCADA	Supervisory Control and Data Acquisition

1 Executive Summary

1.1 Project Background

This document addresses the operational performance and practical experience of several PV plants in Armenia funded by the German Armenian Fund (GAF). Its purpose is to derive lessons learned from operating plants across the full project lifecycle, from permitting and construction to ongoing operation, and to use these findings to improve future project planning and asset reliability.

The survey was carried out in three phases: survey design, data collection, and data analysis/reporting. Questionnaires were aligned with industry standards and covered plant performance, operational challenges, mitigation measures, and failure rates of key components such as modules and inverters. Data collection combined qualitative input from site visits and interviews with quantitative information on failures, maintenance history, and performance trends.

1.2 Grouping of PV Plants

To reflect differences in complexity and operating maturity, plants were grouped by scale and operational characteristics:

- Group 1 - Medium & Large Scale: PV Plants in the range of 1 to 5 MVA_{AC} range, typically commissioned between 2018 and 2022. Within Group 1, the portfolio consists of medium-scale systems of 1 to 2 MVA_{AC} and large-scale systems of 2 to 5 MVA_{AC}. These sub segments also map to program phases: medium-scale projects were primarily financed under Phase III, while the large-scale projects were financed under Phase IV.
- Group 2 - Small Scale: PV Plants in the range of 3.3 to 636 kW_{DC}, comprising 45 plants, typically commissioned between 2021 and 2025.

1.3 Quality of Data

The report considers the overall quality and completeness of the collected data to be good. At the same time, it notes important limitations. Much of the feedback came from EPC companies responsible for plant operation rather than from the plant owners themselves, which introduces a potential self-reporting bias. In addition, detailed failure information for PV components was not complete, so the report does not attempt a full root-cause analysis. Instead, it consolidates available evidence, compares it with general industry experience, and identifies improvement areas for long-term asset management.

1.4 Main Findings

Group 1 – Medium & Large Scale

Overall performance is solid, with reliability and O&M execution emerging as the most important improvement levers. Most plants operate close to expectations, and the observed failure patterns largely align with typical behaviour for plants of comparable age.

- Energy yield is broadly on plan, with only a small share of plants reporting material deviation from expected annual generation; where deviations occurred, they were driven by specific issues such as grid or component events and one case where yield assumptions were overestimated.
- Component sourcing and mechanical integrity are generally strong, with Tier 1 OEM selection standard across the sample, mounting structures demonstrating high reliability, and tracker related issues remaining limited.
- Grid curtailment is currently not a major yield constraint; where reported, its impact on annual production is modest.
- HSE performance and social acceptance are strong, with no incidents reported and consistently positive community relations.
- Satisfaction with the GAF RE funding scheme is universal among respondents, and there is strong interest in future funding, including for renewable generation and BESS projects.

At the same time, several findings require attention.

- Performance monitoring is underutilized. While weather stations are installed at most plants, a significant share does not use the data for performance monitoring, often due to low trust in data quality. This reduces diagnostic capability and can mask underperformance drivers such as soiling, temperature effects, or sensor drift.
- Inverters are the primary availability risk, with frequent failures and material downtime. Many plants mitigate impacts through their own spare parts inventory, which is a positive sign of preparedness, but outages remain consequential and OEM response times vary considerably.
- Grid events are common in occurrence but usually short in duration; nevertheless, individual events can become material when combined with critical component failures, particularly transformers and protection equipment.
- O&M practices and capability constraints persist. Module cleaning is often insufficient, technician availability is a recurring bottleneck, and spare parts strategies vary, with offsite storage distances in some cases risking delayed recovery.

Group 2 – Small Scale

Overall satisfaction is high, but inspection discipline, safety awareness, and minimum engineering diligence are inconsistent and represent the main long term risks in this segment.

- Owners generally report a positive experience, including high satisfaction with installation companies and the decision to invest in PV.
- Monitoring is widespread and user friendly, relying predominantly on mobile apps or inverter displays, which is appropriate for small systems.
- Economic value is evident in qualitative terms, with most owners reporting meaningful savings, reinforcing the attractiveness of PV at this scale.

However, several attention points stand out.

- Inspection discipline is weak, with a notable share of systems reporting that they have never been inspected despite being operational long enough to warrant at least one periodic check.

- Cleaning practices are often subjective and insufficient, with “clean only when visibly dirty” frequently reported, which can lead to avoidable yield losses and delayed detection of developing issues.
- Rooftop engineering diligence varies, as some systems rely only on visual roof checks rather than proper structural assessment, increasing long term structural and waterproofing risk.
- Safety maturity is uneven, with many owners unsure what to look for during safety checks and low adoption of several protective features, indicating a need for clearer guidance and minimum standards.

Priority recommendations

A small number of program level actions would address the main risks while preserving the strong overall performance trend.

- Establish a minimum technical and O&M baseline covering monitoring requirements, inspection frequency, spare parts strategy, and preventive maintenance routines, scaled appropriately for Group 1 versus Group 2.
- In Group 1, treat inverter reliability as the main availability lever through stronger preventive maintenance discipline, critical spares strategies, and clear service response commitments or LTSA structures.
- Convert monitoring assets, especially weather stations, into operational value through appropriate sensor specifications, calibration and cleaning routines, data validation, operator training, and consistent use in performance and loss analysis.
- Address capability gaps by strengthening technician capacity for utility scale plants and owner operator competence for small systems through targeted training and practical checklists and handover packages.
- In Group 2, improve rooftop QA and safety adoption by setting clearer minimum expectations for roof assessment, documentation handover completeness, and baseline protective measures.
- Codify the practices that drove stronger Phase IV outcomes into templates, technical requirements, and contractual obligations so that improvements remain consistent as the program scales.

In summary, it can be concluded that the surveyed PV portfolio in Armenia provides a broadly constructive operational picture, with good data availability, positive owner satisfaction, and generally limited severe technical or regulatory problems. At the same time, the survey identifies clear improvement areas in monitoring practice, safety implementation, maintenance routines, and management processes, particularly for smaller plants, and positions these lessons as a basis for strengthening future PV project development and operation.

A portfolio level learning effect is evident across program phases. The Phase IV large scale plants have, in general, achieved stronger operational outcomes, indicating that improvements in project development and execution were implemented as experience accumulated across earlier phases. This is an encouraging signal for future phases, provided that lessons learned are systematically captured, transferred to owners, EPCs, and operators, and embedded into standard requirements and routine operational practices.

2 Introduction

2.1 Project Background

The project aimed to carry out a detailed survey of several operational PV plants in Armenia funded by the German Armenian Fund (GAF). These plants, ranging from small-scale units of a few kilowatts to medium-scale installations of approximately 1-2 MW, and up to large-scale plants of around 7 MW, can provide valuable operational insights by identifying experienced challenges and by compiling failure statistics. Moreover, by recording lessons learned across the full lifecycle of PV plants, from permitting and construction to operational failures, the survey aims to improve future project planning and enhance asset reliability. The project was developed in the following subsequent three phases.

Phase 1 – Survey Design

- Defined the target audience of the survey results in alignment with GAF.
- Developed detailed questionnaires for PV plant operators covering:
  - General performance metrics
  - Common operational challenges and applied mitigation strategies
  - Failure rates and root causes for PV modules, inverters, and other key components
- Aligned the survey questions with industry standards and relevant literature benchmarks.
- Requested GAF's assistance as a "door opener" to encourage investor cooperation and participation.

Phase 2 - Data Collection

- Conducted site visits and interviews with O&M personnel to gather qualitative data.
- Collected quantitative data on failures, performance trends, and maintenance history.
- Followed-up with clarification questions in order to clarify any open points to the received replies.

Phase 3 - Data Analysis and Report

- Compared collected data and identified potential weak points.
- Summarized lessons learned and actionable recommendations for future projects.
- Compiled findings into a comprehensive report, supplemented with figures and tables.
- Summary presentation to GAF in Armenia on 31.03.26.

2.2 Grouping of PV Plants

The data were collected via questionnaires adjusted in terms of content to the complexity and scale of each project.

Subsequently, for the data analysis, the PV plants were categorized into two main groups based on their installed capacity:

- Group 1 - Medium & Large Scale: PV Plants in two categories: medium-scale systems of 1 to 2 MVA_{AC} (~1-2 MWp) and large-scale systems of ≥ 2 to 5 MVA_{AC} (up to ~7 MWp), comprising 32 plants. the medium scale projects were originally financed under Phase III, while the large-scale projects were

financed under Phase IV of the program.
The operational start dates span from 2018 to 2022.

- Group 2 - Small Scale: PV Plants in the range of 3.3 to 636 kW_{DC}, comprising 45 plants.
  The operational start dates span from 2021 to 2025.

This categorization will be followed in the current report, with Section 3 covering Group 1 and Section 4 covering Group 2 PV plants.

2.3 Quality of Data

Overall, the quality and completeness of the collected data are considered good, with responses received from a total of 77 PV plants.

In most cases, the feedback was provided by the EPC companies responsible after construction for the plant operation rather than by the plant owners. As a result, there is a potential risk of self-reporting or self-serving bias, whereby certain challenges may be underreported. This should be taken into account when interpreting the findings, and is therefore noted as a disclaimer in the current analysis.

Moreover, full details on PV component failures were not provided, so a complete root cause analysis or assessment could not be conducted and was not also the target of this report. Nevertheless, Fichtner consolidated the available information, analysed observed trends, compared them to general industry experience for plants of a similar lifetime and identified opportunities to strengthen asset management and long-term plant performance.

2.4 Structure of the Report

The current report is covering the Phase 3 of the project and is structured as follows:

- Section 3 provides the data analysis and findings for the survey for Group 1 plants.
- Section 4 provides the data analysis and findings for the survey for Group 2 plants.
- Section 5 presents the main findings of the current survey in order to be taken into account into future financing endeavours, PV plant design and operation.

3 Analysis of Group 1 - Medium & Large Scale PV Plants

3.1 Sample Overview of Group 1

3.1.1 Plants Installed AC Capacity

The survey investigated 32 plants with the installed AC capacity values ranging from 1.0 to 5.0 MVA_{AC} as presented in Figure 1.

- The 1.00–2.0 MVA_{AC} tier comprises 9 plants.
- The 2.01–3.0 MVA_{AC} tier has no representatives in the sample.
- The 3.01–4.0 MVA_{AC} tier includes 2 plants.
- The 4.01–5.0 MVA_{AC} tier includes the highest number of plants in the sample, totalling 21 plants.

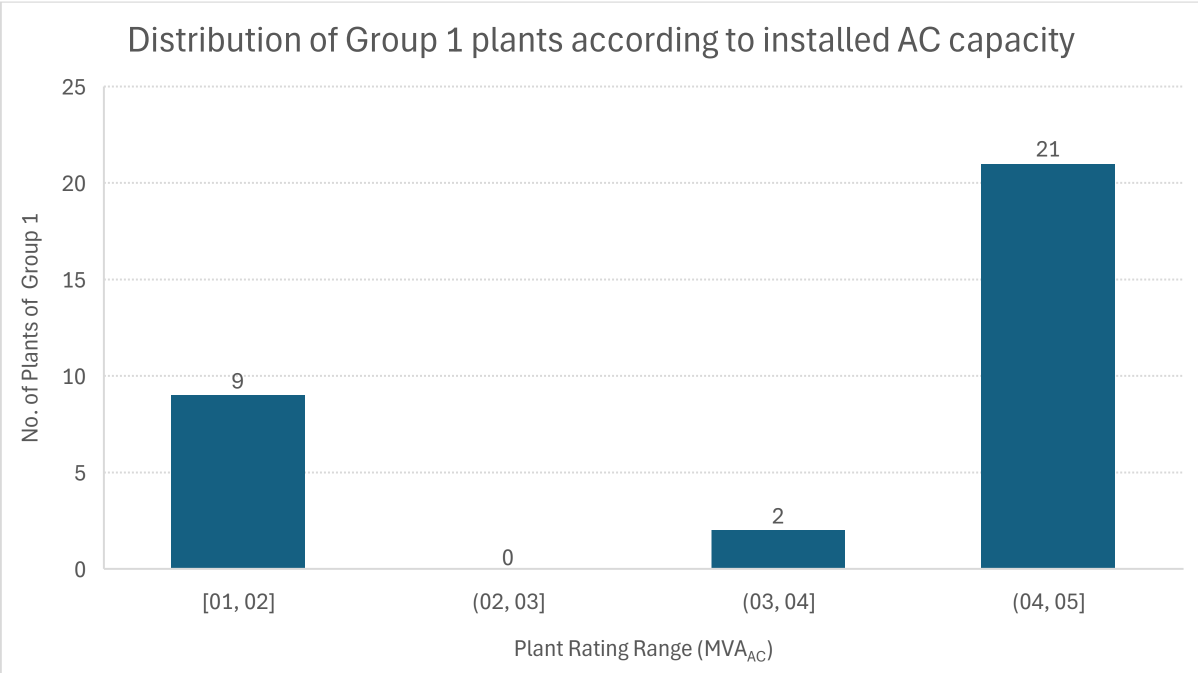

Figure 1: Distribution of Group 1 plants according to AC installed capacity

3.1.2 Selection of OEM for PV Modules and Inverters

In terms of PV modules, the most frequently selected Original Equipment Manufacturer (OEM) was LONGi (9 plants), followed by Risen Energy (8), Jinko Solar (5), PhonoSolar (3), Tongwei (2), Talesun (2), AE Solar (1), and Luxen Solar (1).

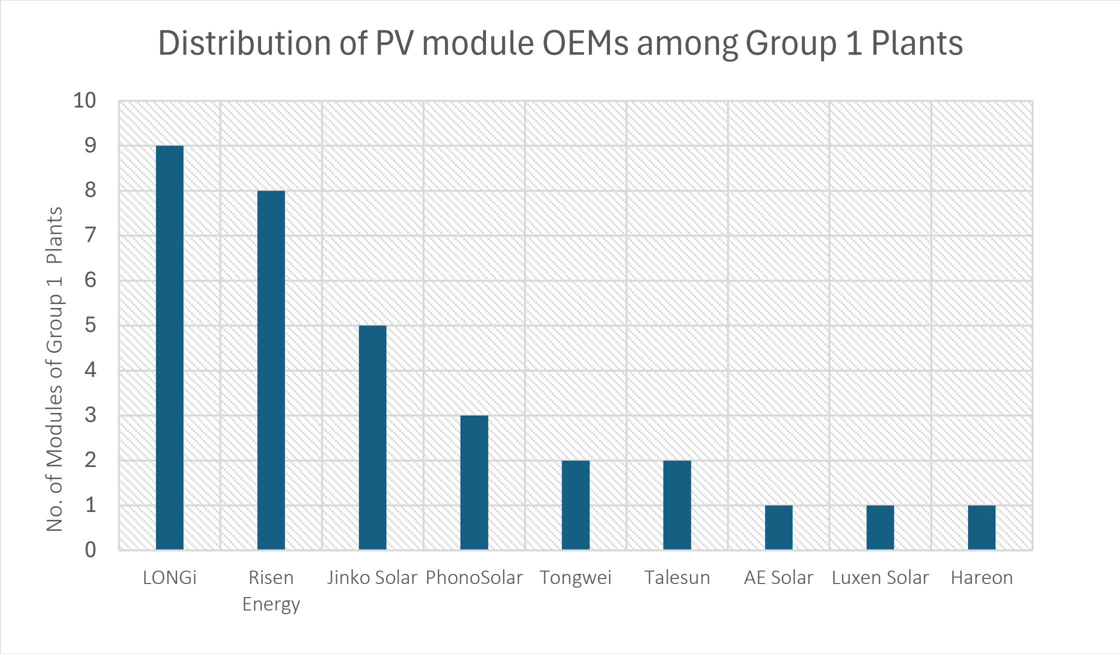

Figure 2: Distribution of PV module OEMs among Group 1 plants

With respect to inverters, Huawei dominated the selection, being deployed in 23 plants. KSTAR was selected for 8 plants, while Ingeteam supplied 1 plant.

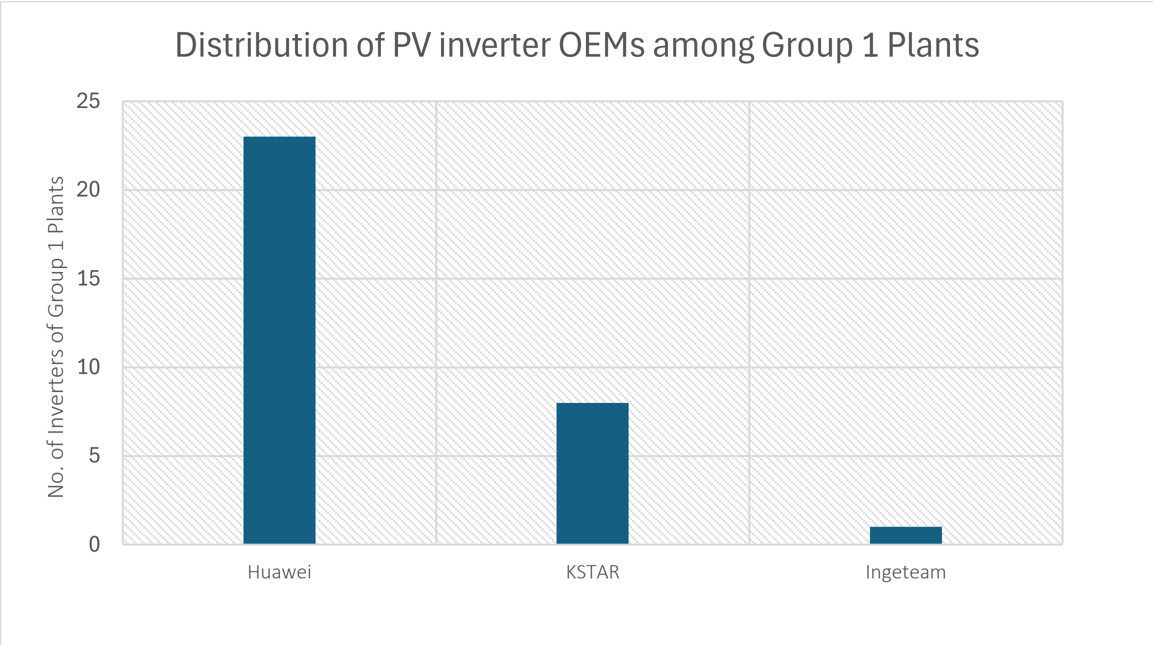

Figure 3: Distribution of inverter OEMs selected among Group 1 plants

Overall, the selection of module and inverter manufacturers for the project aligns with current market trends, predominantly utilizing Tier 1 suppliers to ensure high-quality and reliable components. Furthermore, the Chinese OEMs dominate both the module and the inverter selection. Single exception is one case in which a Spanish OEM (Ingeteam) was chosen as an inverter supplier.

3.1.3 Mounting System and Foundation

Among the PV plants of the group, 25 were of fixed tilt, with a tilt angle between 23° and 37°. Seven plants had a single axis tracker.

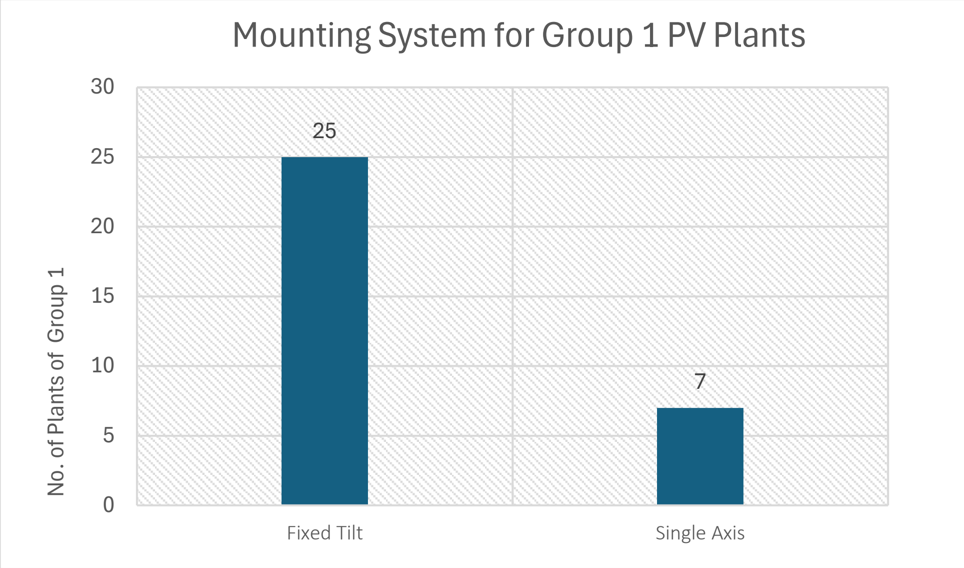

Figure 4: Mounting system of the PV plants of Group 1

All fixed-tilt plants were supported by cast-in-place concrete piles, with the exception of two sites that used steel posts driven into soil or concrete. All single-axis tracker plants were supported by steel posts driven into soil or concrete.

3.2 Energy Production Performance

3.2.1 Weather Station

Among the 32 PV plants, 27 are equipped with a weather station.

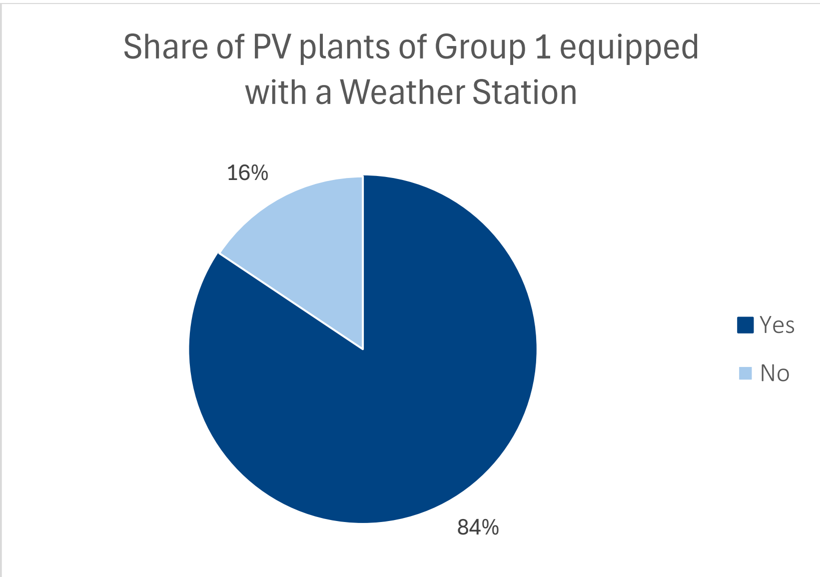

Figure 5: Share of PV plants of Group 1 equipped with a weather station

Global Horizontal Irradiance (GHI), ambient temperature, wind speed/direction, and relative humidity are consistently monitored across 27 out of 32 plants, reflecting their critical role in assessing plant operation and energy yield.

Less common are the measurements of Global Inclined Irradiance (GII) (5 plants), module temperature (4 plants), while PM10, PM2.5, and rain/snow transmitters are only monitored in 3 plants each. This distribution indicates that while basic environmental monitoring is widespread, more detailed or site-specific measurements remain limited across the portfolio. In particular, module temperature monitoring is crucial for detecting potential operational issues, as deviations in module temperature can signal underperformance, thermal stress, or early signs of component failure.

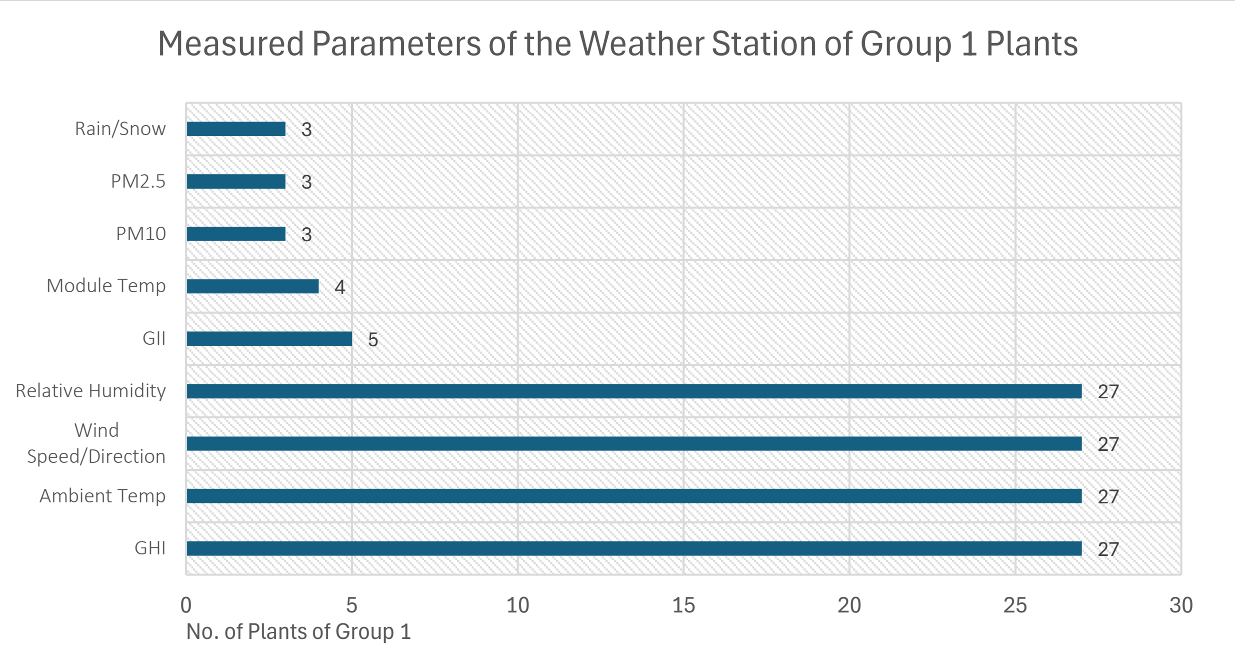

Figure 6: Measured parameters of the weather station of the PV plants of Group 1

Although weather stations are installed at the majority of the plants as explained above, 12 of them (44%) are not used for performance monitoring. As a result, the potential added value of correlating plant performance with local meteorological data is not fully exploited. This gap has several impacts. Without using on-site weather data, performance assessments rely more heavily on modelled or satellite-derived irradiance, which introduces additional uncertainty and can mask real operational issues. It also limits the ability to detect underperformance caused by environmental factors such as soiling, shading, or abnormal temperature behaviour. Furthermore, the absence of real-time meteorological inputs reduces the accuracy of performance ratio calculations and weakens the basis for predictive maintenance, making it harder to identify early signs of degradation or component failure. In practice, this means that plants may appear to perform normally while subtle but important losses remain undetected.

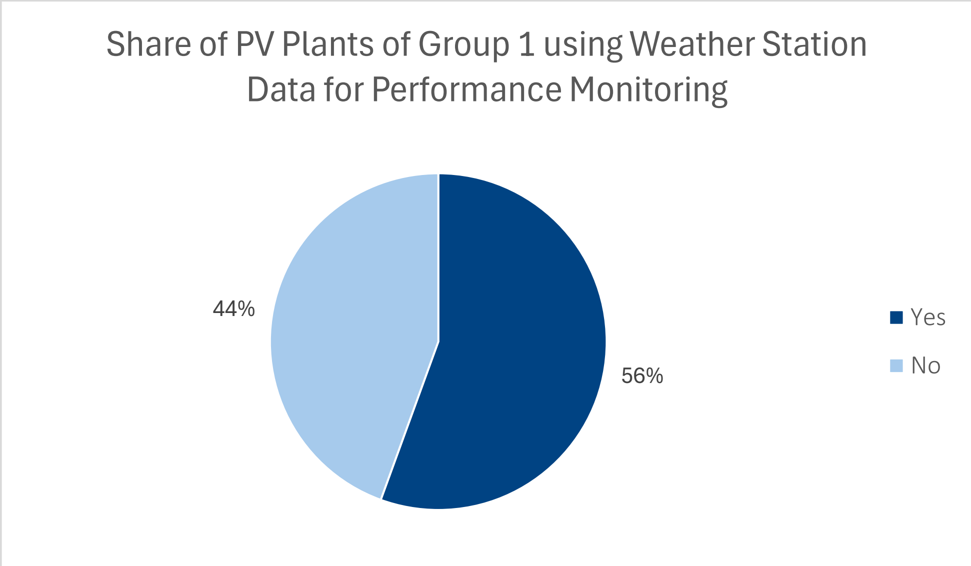

Figure 7: Share of PV Plants using Weather Station Data for Performance Monitoring

Regarding the reliability of the weather stations, the overall assessment is not particularly positive: 10 plants consider the data fully reliable, while another 10 consider it not reliable at all as presented in Figure 8. Notably, plants reporting unreliable data also stated that they do not use the weather station for performance monitoring, indicating a lack of trust in the provided information. Additionally, there are 6 plants declaring that the data are somewhat reliable and 1 plant not sure about their reliability. For monitoring system applied for plant performance data, almost all the PV plants use the Inverter manufacturer's monitoring platform, with the single exception being one plant having a customized in-house solution.

Low confidence in data quality further discourages operators from integrating meteorological information into performance analysis, reinforcing the underuse of an otherwise valuable asset.

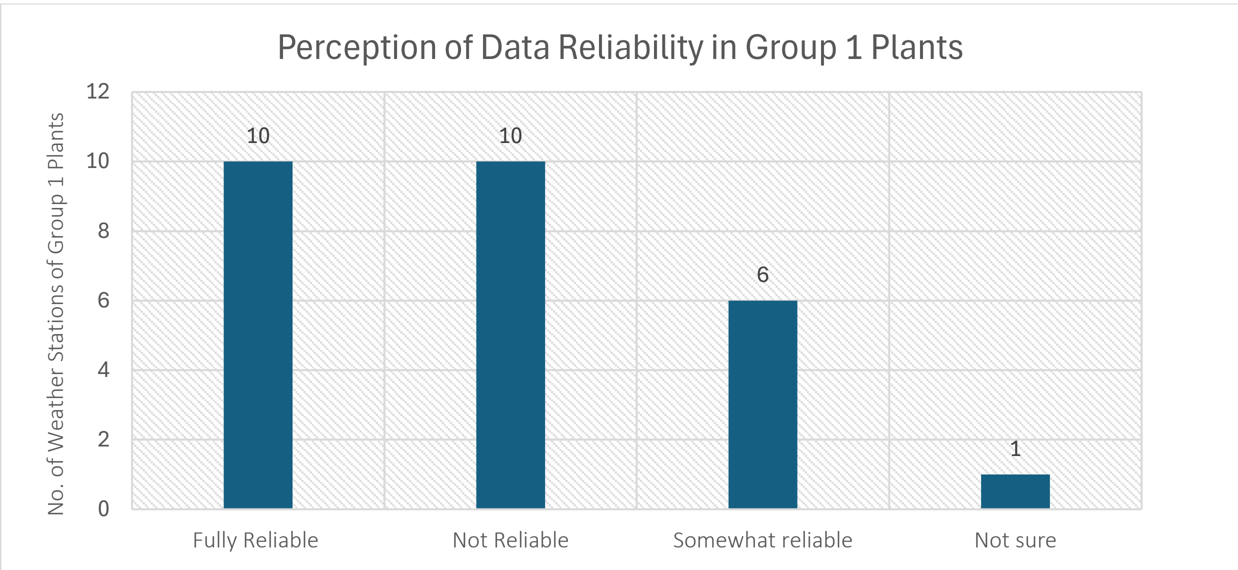

Figure 8: Perception of Data Reliability in Group 1 Plants

Although a significant share of the surveyed PV plants reported that weather-station data is perceived as unreliable, the specific root causes of this mistrust were not disclosed by the operators. Nevertheless, industry experience and common issues observed in PV monitoring systems allow us to identify several likely sources of data unreliability, as well as measures to prevent these challenges in future projects. Some key reasons for mistrusting weather station data are:

- Sensor degradation / poor calibration
- Incorrect installation and shading issues
- Insufficient cleaning and maintenance
- DAQ/SCADA errors and communication problems
- Low-quality or inappropriate sensors
- Data inconsistencies or gaps
- Lack of redundancy or benchmarking
- Operator unfamiliarity or lack of trust
- Misalignment between measured data and plant behaviour

To ensure weather-station data is reliable and trusted, the following good practices are recommended:

- Specify High-Quality Sensors
  - Use secondary-standard pyranometers for GHI/GII measurements.
  - Select robust, accurate temperature probes with proper mounting methods.
  - Ensure that all sensors comply with IEC standards (e.g., IEC 61724-1).
- Ensure Proper Installation and Positioning
  - Level and align irradiance sensors according to manufacturer specifications.
  - Select representative, unobstructed locations for all measurements.
  - Install module temperature sensors with good thermal contact and shielding from direct sunlight.
- Define a Comprehensive O&M Plan for Meteorological Equipment
  - Regular cleaning schedule for pyranometers (weekly to monthly, depending on site conditions).
  - Annual or biannual calibration or recalibration checks.
  - Periodic functional testing of anemometers, humidity sensors, and temperature probes.
- Improve Data Quality Through SCADA Validation
  - Implement automated data plausibility checks (range, consistency, spike detection).
  - Ensure correct scaling factors, units, and logging intervals.
  - Provide redundancy for critical signals (e.g., using inverter irradiance sensors for cross-checks).
- Provide Operator Training including:
  - Sensor operation principles
  - Typical failure modes
  - Data interpretation techniques
  - Use of meteorological data for performance analysis
- Integrate Benchmarking and Cross-Validation
  - Periodically compare on-site data with external reference datasets (e.g., satellite irradiance).
  - Use analytical tools to correlate plant performance with weather parameters.

Such practices can significantly improve the quality and reliability of meteorological measurements and ensure their effective integration into performance monitoring.

3.2.2 Deviations from Expected Performance

Overall, the plants performed largely as planned, with only 3 plants (9.4%) deviating from the expected annual generation, two negatively and one positively, indicating that the expected performance closely matched the actual production. The magnitude of these deviations and the underlying reasons are presented in Table 1.

No	Deviation from Expected Performance	Reasoning
1	25-30% (negative)	▪ Grid connections issues (emergency shutdowns) ▪ Component failures (transformers)
2	17% (negative)	▪ Overestimated yield
3	5% (positive)	▪ More favourable weather conditions during last 3 years. ▪ Conservative input data used in the initial PVsyst simulation compared to actual conditions. ▪ Lower-than-expected transmission line losses.

Table 1: Plants with deviations from expected performance and associated reasoning

The results of the survey highlight the critical importance of developing accurate and realistic energy-yield assessments during the design phase. As seen in the few plants that deviated from expectations, particularly the case of overestimated yield, incorrect or overly optimistic assumptions can lead to significant operational and financial consequences. Overestimating production may result in plants appearing underperforming during operation, triggering unnecessary investigations, contractual disputes, or perceived efficiency losses. Conversely, inaccurate modelling can also contribute to oversizing certain components, inflating CAPEX without delivering proportional energy gains. These deviations illustrate how essential it is to rely on robust modelling practices, validated input data, and conservative assumptions to ensure that long-term performance aligns with forecasts. Strengthening yield-assessment methodologies not only reduces uncertainty but also supports more efficient plant design and more reliable performance expectations throughout the project lifetime.

3.3 Component Failures

This chapter provides an overview of the component-related failures reported across the surveyed PV plants, with the objective of highlighting recurring issues, raising awareness of the most critical failure modes, and supporting the improvement of O&M practices and mitigation strategies. When interpreting the reported failures, it is important to consider that not all issues carry the same severity, operational impact, or underlying causes. Some failures are inherent to large-scale manufacturing—where a certain defect rate is statistically expected—while others relate to early-life ("infant mortality"), mid-life degradation patterns, or wear-out mechanisms typically observed over the operational lifetime of PV components (e.g. ≥25 years for PV modules and ~10–15 years for inverters). These contextual factors are essential for correctly assessing the frequency and relevance of each failure type.

Furthermore, as the survey consolidates information provided directly by plant operators, detailed root-cause analyses or precise operating conditions were not always available. Consequently, while the Section summarizes the trends observed, it does not intend to deliver an in-depth forensic assessment of the failures. Instead, it offers a structured overview of the issues encountered in modules, inverters, mounting structures, trackers, and other electrical components, serving as a baseline for understanding reliability challenges and identifying opportunities to strengthen asset management and long-term plant performance.

3.3.1 Modules

A total of 37% of the surveyed PV plants reported failures in their PV modules. This proportion does not, based on the available information, suggest an abnormal deviation from general industry experience. However, as the survey relies on operator-reported data and often lacks detailed diagnostics, the severity of these failures cannot be precisely assessed. Without systematic root-cause analysis, it is also not possible to clearly distinguish between contributing factors such as installation quality, manufacturing variability, climatic conditions, or ageing effects.

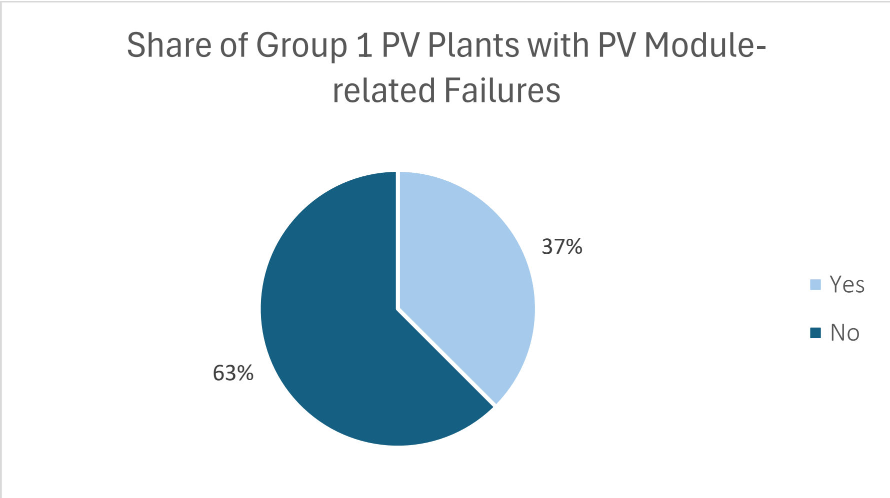

Figure 9: Share of Group 1 PV Plants with PV Module-related Failures

Broken glass is the most frequently reported issue, accounting for 31.25% of all failures. Connector and cable defects, together with junction box failures, follow with 25% each, highlighting recurrent challenges in the electrical balance-of-system components. Less common issues include cell cracking or microcracking at 12.5%, while lightning-related damage represents the remaining 6.25% of reported failures.

Overall, the reported failures are consistent with the types of issues typically observed in utility-scale PV systems of comparable age. For plants operating between 4 and 8 years, it is expected that early field degradation phenomena begin to appear, particularly in components such as connectors and junction boxes, which are known to be among the most common sources of reliability problems in the industry.

Likewise, occasional glass breakage or weather-related mechanical damage is not unusual at this stage of operation.

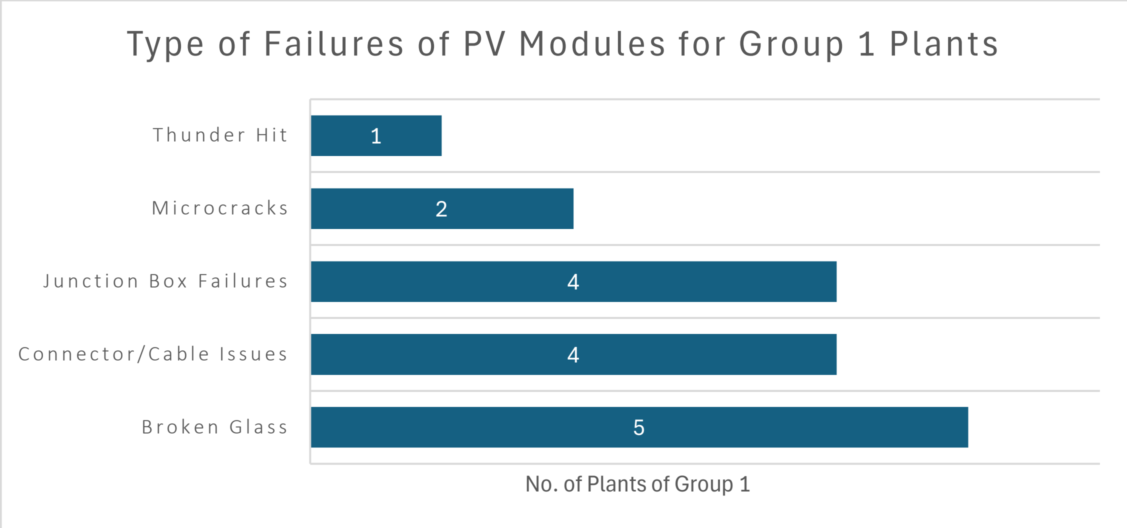

Figure 10: Type of failures of PV modules for Group 1 Plants

The majority of module failures were identified through visual inspections, reported in 8 plants, confirming that many issues manifest physically before they appear in system data. In contrast, performance-monitoring analytics and inverter malfunction alerts each accounted for 2 cases, indicating that only a smaller portion of failures were detected indirectly through operational performance deviations or electrical system disturbances.

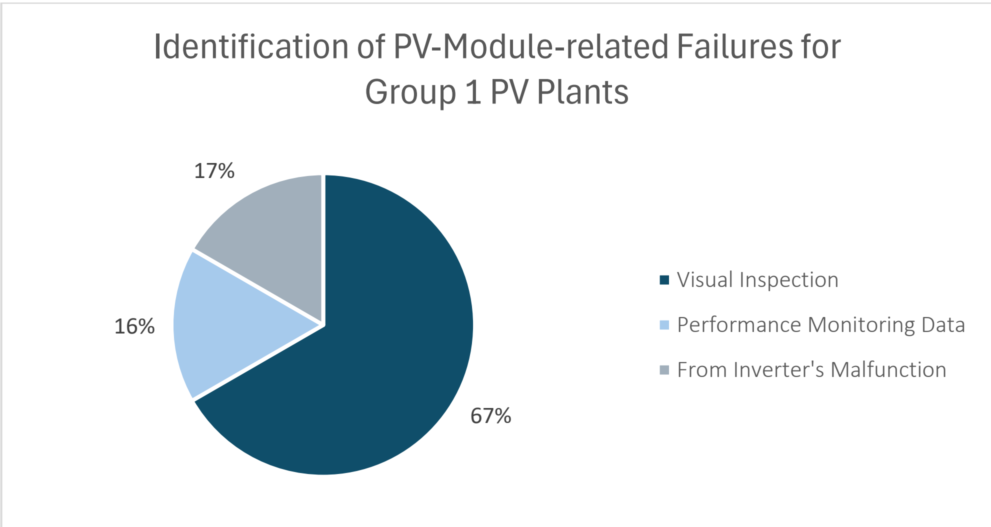

Figure 11: Identification of failures of PV modules for Group 1 PV Plants

Only two of the reported failures (16%) resulted in warranty or insurance claims. In both cases, the manufacturers reacted promptly, initiating corrective actions within 5 and 7 days, respectively.

In summary, to reduce the occurrence of similar module-related failures, it is advisable to reinforce installation and handling practices, particularly for connectors, junction boxes, and glass-exposed components. Regular visual inspections, complemented by periodic thermographic checks, can help identify early signs of overheating, loose contacts, or developing physical defects. Ensuring the use of compatible connector types and proper mating procedures during installation and repairs can prevent many electrical issues. Keeping a limited stock of spare modules that match the original bill of materials can also shorten repair times and maintain system consistency. Strengthened documentation of module issues will support trend analysis and improve future procurement decisions.

3.3.2 Inverters

More than half of the plants experienced significant inverter failures, as shown in Figure 12, indicating that inverter-related issues are among the most common sources of operational disruptions. The findings align with industry-wide observations that inverters remain the component most prone to early-life failures and operational disruptions. Specifically, for plants operating between 4 and 8 years, a measurable number of inverter failures is not unexpected, as this period often captures the transition from early-life to mid-life reliability behaviour.

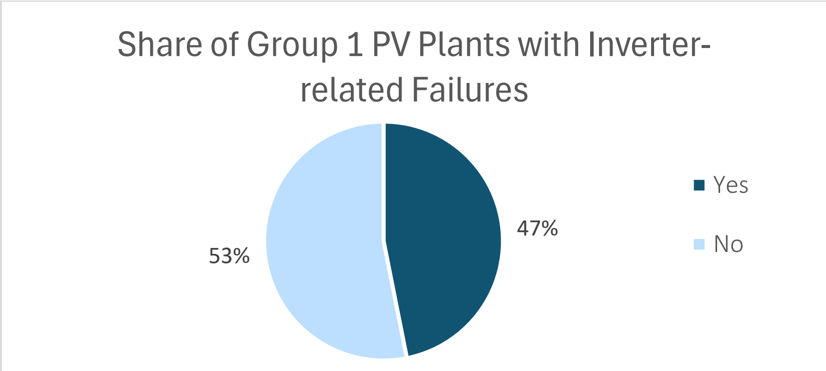

Figure 12: Share of Group 1 PV Plants with inverter-related failures

Circuit board failures were by far the most common issue, followed by failures in power electronic components, which shows that electronic and control-related parts are the main drivers of reliability concerns. Other problems such as cooling, software, communication or protection device issues occurred only sporadically across the surveyed PV plants. In general, the predominance of circuit-board and power-electronics problems reflects common stress mechanisms associated with thermal cycling, inadequate ventilation, component ageing, and, in some cases, installation or configuration deficiencies.

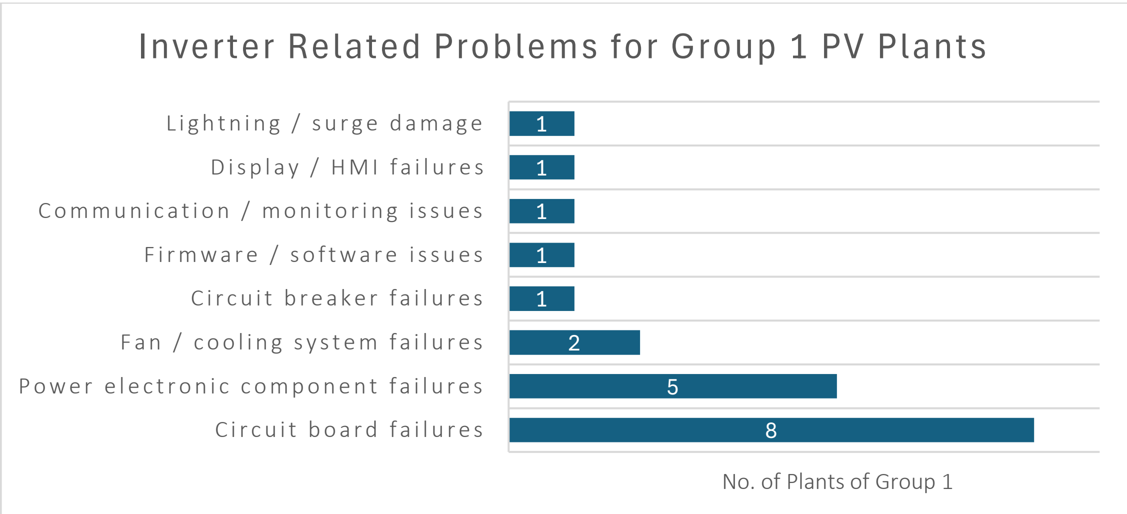

Figure 13: Inverter related problems for Group 1 PV Plants

From a design perspective, inverter failures often stem from insufficient thermal management, inadequate ventilation, or incorrect sizing relative to site-specific operating conditions, all of which can place continuous stress on sensitive power electronics. In terms of component selection, choosing inverters that are not fully certified for local climatic conditions, or opting for models with limited field reliability data, can significantly increase the likelihood of early-life or recurring failures. Operational practices may also play a role: issues such as delayed corrective maintenance, poorly executed preventive inspections, or incorrect installation procedures—including torque errors, cabling mistakes, or inadequate grounding—can lead to accelerated wear, electrical stress, or protective shutdowns. Together, these factors suggest that the reported inverter failures might not be isolated incidents, but rather symptomatic of broader challenges in engineering design, procurement decisions, or O&M execution across the surveyed plants.

The average downtime caused by inverter failures was 12.2 days, which shows that such events can significantly disrupt plant operation and therefore reduce electricity production and revenues.

On a positive note, 14 out of the 15 affected plants were able to replace the failed components using their own spare-parts inventory, demonstrating effective spare-parts planning and preparedness for corrective maintenance.

Regarding OEM warranties, these were fully honoured in all reported cases. The response times of the manufacturers ranged from 2 to 60 days, with an average of 27 days, indicating generally adequate although sometimes highly variable support.

Given the frequency and impact of inverter failures, more systematic preventive maintenance would help reduce downtime. This includes routine checks of cooling systems, ventilation paths, and filter conditions, as well as verification of cable terminations and grounding. Establishing a structured process for firmware updates (e.g. tested on a limited number of units before wider rollout) can reduce the risk of software-related interruptions. Maintaining adequate stocks of critical spare parts such as control boards or fans enables faster corrective interventions. Enhanced monitoring of inverter operational parameters can also support earlier detection of abnormal behaviour.

3.3.3 Mounting Structures and Trackers

No issues related to mounting structures were reported among the 32 surveyed plants. This suggests that structural components have generally performed reliably within the 4–8-year operational window. This result aligns with expectations, as mounting structures, when properly designed and installed, typically exhibit low failure rates during early and mid-life operation, with most issues emerging only under extreme weather events or long-term corrosion processes.

Among the seven plants equipped with tracker systems, only one reported a failure, specifically involving the control system. Given the mechanical and electronic complexity of tracker systems relative to fixed structures, isolated control-related issues are not uncommon and do not indicate systemic reliability concerns.

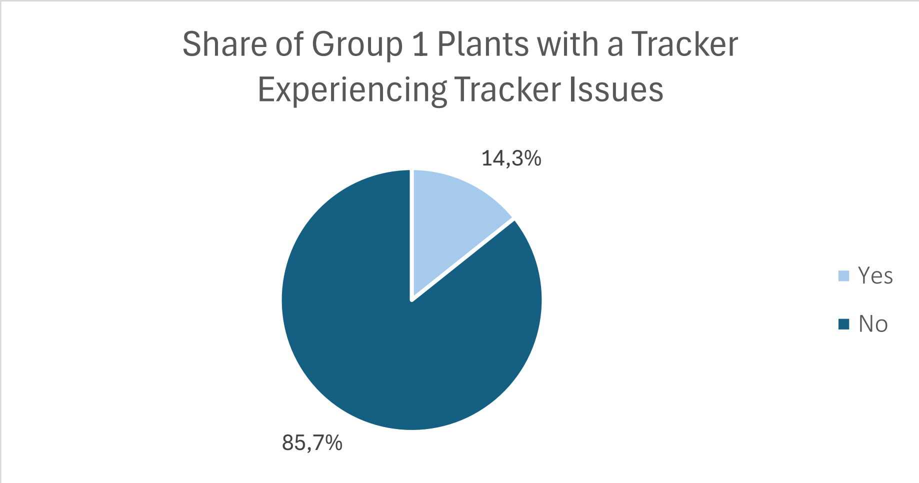

Figure 14: Share of Group 1 PV plants with a tracker experiencing tracker issues

In summary, the structural and tracking systems in the surveyed plants appear to be performing within normal industry expectations. Nevertheless, periodic mechanical inspections remain important to ensure long-term stability. Torque checks on clamps and bolts, alongside routine corrosion observations, should form part of the regular maintenance cycle. For tracker systems, verifying the condition of control components, communication links, and protective enclosures can help avoid control-related malfunctions. Seasonal inspections, as well as post-weather-event checks, are recommended to maintain consistent tracking performance and reduce the likelihood of operational disturbances.

3.3.4 Rest of Components

Transformer issues were encountered in four plants, representing 12% of the PV plant sample as presented in Figure 15. The reported issues were as follows:

- Transformer was replaced because it was operating under a 34% overdrive
- Transformer was replaced due to damage by overcurrent.
- The gas protection system of the transformer was activated several times due to unstable grid (voltage fluctuations and harmonics).
- Transformer insulators were replaced under warranty.

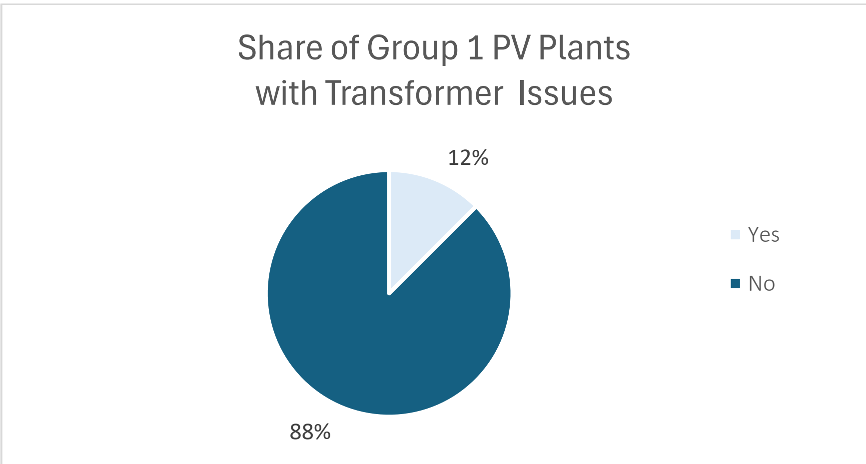

Figure 15: Share of Group 1 PV Plants with transformer issues

In terms of switchgear and protection equipment, issues were reported in 5 plants (16%). In three of these cases, switchgear units required replacement, with the number of affected units ranging from two to five. Another plant experienced connector problems within the protection system, while one facility faced recurrent fuse failures occurring on a monthly basis. Fortunately, the necessary replacement fuses are kept in stock at the warehouse, which helped minimize downtime.

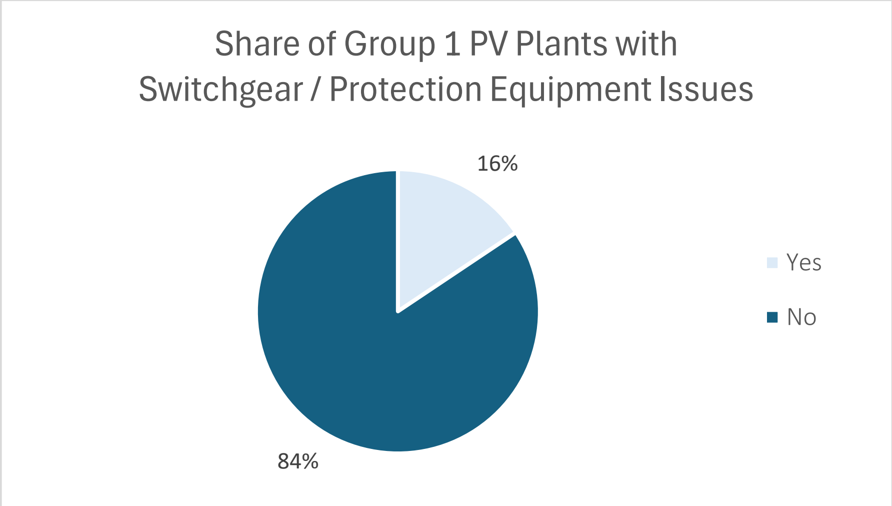

Figure 16: Share of Group 1 plants with switchgear / protection equipment issues

Regarding the SCADA system, a total of 4 malfunctions were reported. In two of these cases, updates to the software and the related application caused the monitoring system to remain unavailable for two full weeks in 2024. Another plant experienced voltage levels exceeding the permissible limit, which required formal communication with the Electric Networks of Armenia to resolve the situation. In the final case, the facility encountered an issue related to a connector within the SCADA system.

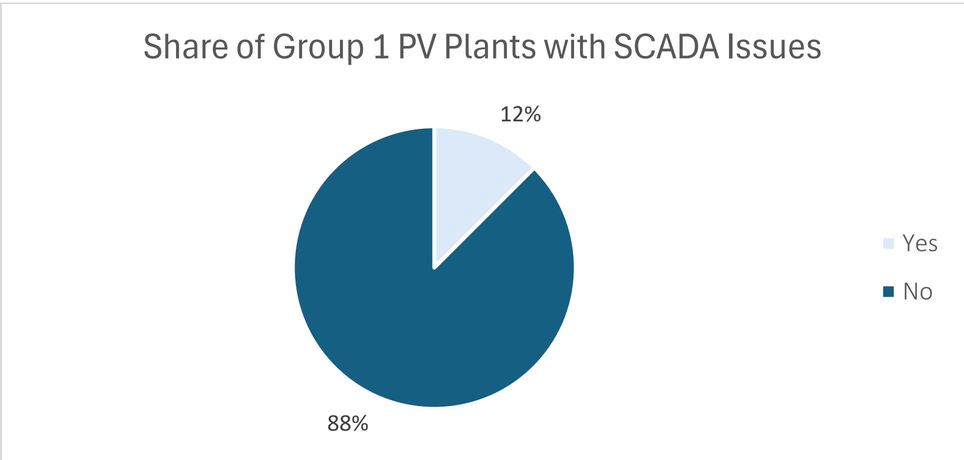

Figure 17: Share of Group 1 PV Plants with SCADA Issues

Failures reported in transformers, switchgear, protection devices, and SCADA systems were relatively limited in number but point toward a recurring pattern linked to grid-quality challenges, particularly voltage fluctuations and harmonics. Several transformer issues ranging from overcurrent damage to the activation of protection systems, appear to be influenced by unstable grid conditions rather than intrinsic equipment design flaws. Likewise, SCADA malfunctions caused by software updates and excessive voltage levels further indicate the operational impact of external grid behaviour on plant performance.

Switchgear and protection-related failures, including repeated fuse replacements and connector faults, generally fall within typical mid-life operational issues for plants in the 4–8-year age range. These components are sensitive to installation quality, environmental stress, and load fluctuations, and the reported issues do not suggest abnormal deterioration. The availability of replacement parts and on-site responsiveness helped to limit operational downtime in most cases.

Overall, the failures in these electrical components appear broadly aligned with what would be expected across similar utility-scale assets, though the influence of grid instability is a notable external factor. Strengthening coordination with the grid operator, improving monitoring of power-quality events, and reinforcing preventive maintenance on protection systems may reduce the likelihood and impact of similar issues in the future.

For transformers, switchgear, protection devices, and SCADA systems, a combination of targeted inspections and improved monitoring can help prevent similar failures. Periodic checks of protection settings, temperature conditions, and mechanical integrity are recommended to reduce the risk of operational disturbances. Implementing basic power-quality monitoring may help operators identify voltage fluctuations or harmonics that could affect transformer protection or SCADA stability. For switchgear and SCADA equipment, maintaining spare components and following structured software or configuration update procedures can help minimize downtime and improve system reliability.

3.4 Operation and Maintenance

3.4.1 Module Cleaning

In PV plants, the modules gradually accumulate soiling such as dust, dirt, pollen, and bird droppings. As a result, cleaning is applied to prevent energy production losses, which can be in the range of 1-5%, depending on the region. Among the operational plants included in this survey, 17 do not perform any cleaning activities. Of the remaining plants, 9 carry out cleaning based on performance data, while 6 conduct scheduled cleanings twice per year.

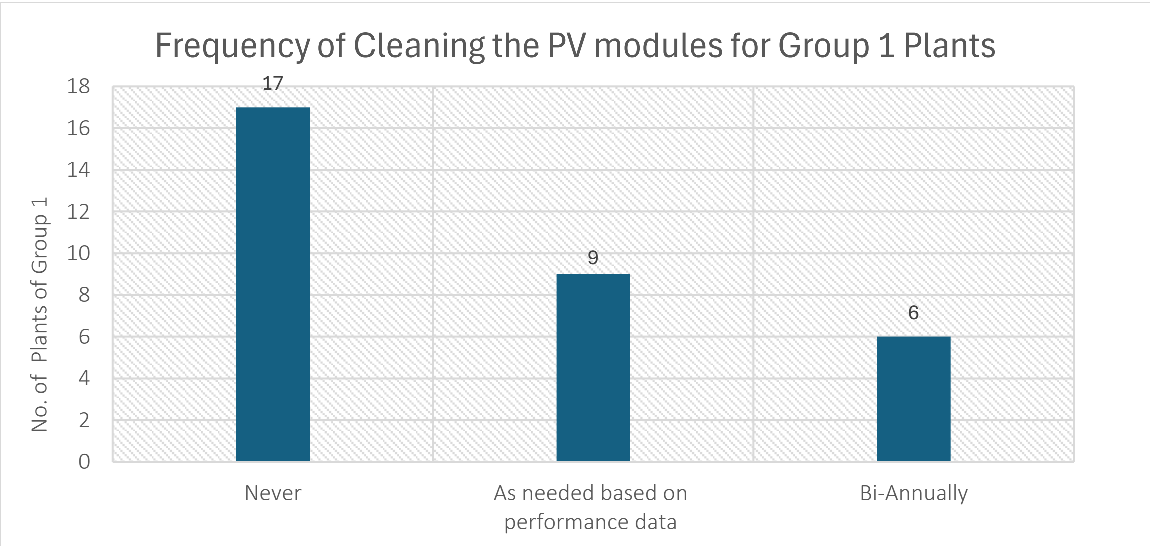

Figure 18: Frequency of cleaning the PV modules for Group 1 plants

The required cleaning frequency for solar PV modules generally varies from plant to plant since it depends on the exact location as well as the climatic and site conditions.

Some typical recommendations are presented below:

- Clean 2 to 4 times annually for most of the sites.
- Higher-dust areas (common in many regions of Armenia) will probably require 4 to 6 times annually.
- More often if the site is near construction, unpaved roads, or agricultural land.
- Less often in rainy region due to natural cleaning.
- Snow usually melts on its own, but light manual clearing may be needed in winter if heavy snow cover persists for several days since it lead to additional load on the modules.

Parameters to be taken into account when deciding on the right frequency of cleaning the modules are indicated below:

- Dust and pollen levels.
- Nearby traffic or industry.
- Bird activity.
- Air pollution in urban areas.
- Tilt angle (flatter panels need more cleaning).
- Rule of thumb: If energy production drops by more than 5 to 7 percent compared to expected output (and no technical faults exist), cleaning is likely needed.

Among the plants that perform cleaning, the most commonly used method is manual wet cleaning, applied by 9 plants. This is followed by the use of sun-brush cleaning machines, which are employed at 6 plants. In addition, one plant uses manual dry cleaning, while another plant does not apply any active cleaning method and instead relies on natural cleaning through snowfall.

It should be noted that proper cleaning is essential, as incorrect practices can lead to damage. Moreover, while wet cleaning is an effective and quick solution, the use of water in water-scarce regions is neither sustainable nor recommended.

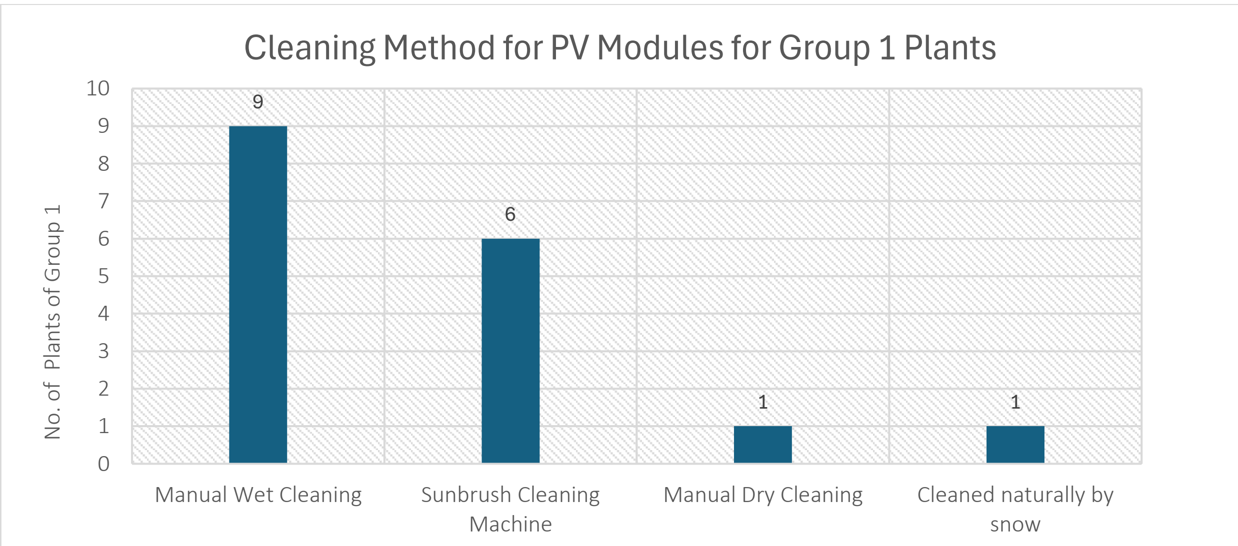

Figure 19: Cleaning methods used for the PV modules of Group 1 plants

Regarding soiling losses, 26 plants (82%) reported no significant impact from soiling, while 6 plants (approximately 18%) experienced losses in the range of 2.5 to 3%, despite performing biannual cleaning with a sun-brush machine.

Overall, the fact that more than half of the PV plants (52%) do not apply any cleaning method is not a positive finding. Regular cleaning supports efficient electricity production and is a relatively simple activity that also contributes to maintaining the modules and associated equipment in good condition.

3.4.2 Vegetation Management

The survey indicates that vegetation management is actively implemented in all PV plants where such measures are necessary. As shown in Figure 20, the most common approach is a combination of regular mowing or cutting together with grazing, applied in 15 plants. This is followed by regular mowing or cutting alone, practiced in 7 plants. Grazing only and mowing combined with herbicide application are less common and are each used in 3 plants.

In general, vegetation management is essential for several reasons. Primarily, it prevents shading, which not only reduces energy production but also mitigates the risk of hotspots on PV modules that can lead to premature failure (an effect that can reduce string output by 10-30% when even a single cell is shaded). Additionally, effective vegetation control enhances safety by minimizing the presence of dry vegetation, particularly during the summer months, thereby reducing fire risk in areas where unmanaged plant growth can act as fuel for ignition sources. Beyond these immediate operational concerns, proper vegetation management helps stabilize soil and limit erosion, supporting long-term site integrity and reducing maintenance challenges that often escalate when vegetation is neglected.

Regarding best practices of vegetation management, for mowing, equipment should be chosen carefully to minimize risks. Certain types of mowers can throw small stones or debris toward PV modules, potentially causing damage.

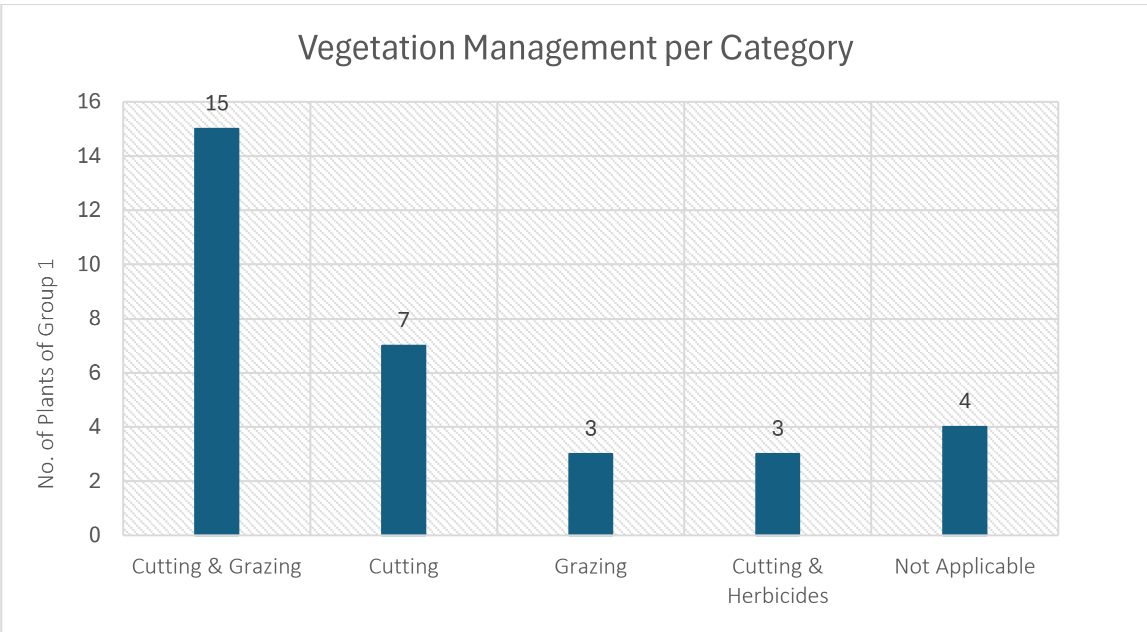

Figure 20: Vegetation management per category for Group 1 plants

Lastly, in terms of vegetation management frequency, practices vary across the PV plants. On average, vegetation control is carried out approximately 2.2 times per year, with reported frequencies ranging from once per year to biweekly interventions during summer, which corresponds to up to six times per year.

3.4.3 Spare Parts Stocks

Half of the plants store their spare parts offsite, which is generally not problematic when the storage location is close to the facility. However, the survey revealed distances ranging from 2 km to as far as 120 km, and in 8 cases the storage site was located more than 50 km from the plant. Such distances can delay response times in the event of component failures that require immediate replacement. In addition, 5 plants manage spare parts both on-site and off-site, while another 5 plants keep all spares exclusively onsite. Finally, 6 plants do not store any spare parts at all, as their full O&M activities are outsourced to external service providers.

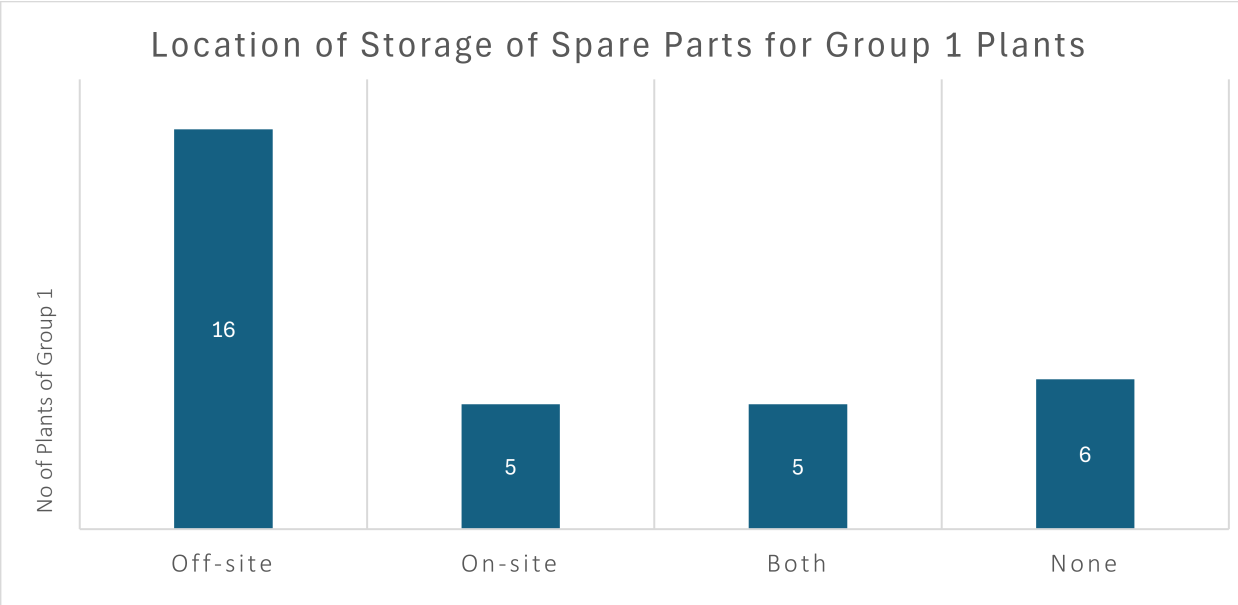

Figure 21: Location of storage of spare part for Group 1 plants

Regarding the two main categories of equipment, namely PV plant equipment and HV substation equipment, the storage of their respective spare parts across the surveyed plants is presented Table 2.

Storage of Spares	PV Plant Spares	HV Substation Spare
Yes	21	16
No	0	5
Not Aware	5	5
None	6	6

Table 2: Storage of spares per equipment category for Group 1 plants

There were 5 cases in each equipment category in which the respondents were not aware whether storage reserves were being kept. In addition, 6 cases in each category reported that no reserves are stored, since the entire O&M process is outsourced, as explained above.

For PV plant equipment, 21 plants maintain spare parts such as modules, support structures, and inverters. In contrast, for HV substation equipment, this number decreases to 16 plants, indicating lower availability of reserves for high-voltage components.

Overall, the survey reveals a wide variation in spare-parts storage practices across the plants, with approaches ranging from fully on-site storage to complete reliance on outsourced O&M providers. While storing spare parts off-site is acceptable when distances are short, several plants keep their inventories more than 50 km away, which can significantly delay corrective actions for failures that require immediate replacement. The situation is similar for both PV plant equipment and HV substation components, where a notable number of plants either do not maintain reserves or are unaware of their storage status. Such gaps can increase downtime and complicate maintenance planning, particularly for components that fail more frequently or are essential for rapid restoration of production.

In general, the presence and location of spare-parts inventories should reflect the criticality of the equipment. Fast-moving or time-sensitive items, such as fuses, connectors, inverter consumables, and SCADA communication modules, are best stored on-site to ensure immediate availability. Larger or less frequently replaced components can be kept off-site, provided they are stored within reasonable distance (less than ~25 km) and supported by clear response-time commitments from service providers. For plants that fully outsource their O&M, the absence of on-site stock is not uncommon, but it must be compensated by robust service-level agreements and verifiable inventory availability.

Overall, harmonizing spare-parts strategies would enhance operational readiness. Establishing minimum on-site stock levels for critical items, ensuring that off-site storage remains within practical reach, and strengthening contractual requirements for outsourced O&M providers would help reduce downtime and support more consistent maintenance performance across all facilities.

3.4.4 Effective Handling of O&M

When asked which O&M practices proved most effective for the operation of the PV plants, the respondents provided the answers presented in Figure 22.

The results show that effective O&M relies primarily on continuous monitoring and control of plant operations, which enables early detection of anomalies and timely corrective actions. Preventive maintenance is also highly valued, as it helps minimizing unexpected failures and reduces the need for reactive interventions. Respondents also emphasized the importance of prompt resolution of any issues to prevent secondary damage or escalation. In addition, module cleaning and drone inspections were identified as practices of high relevance, contributing to sustained performance and improved fault identification across the PV arrays.

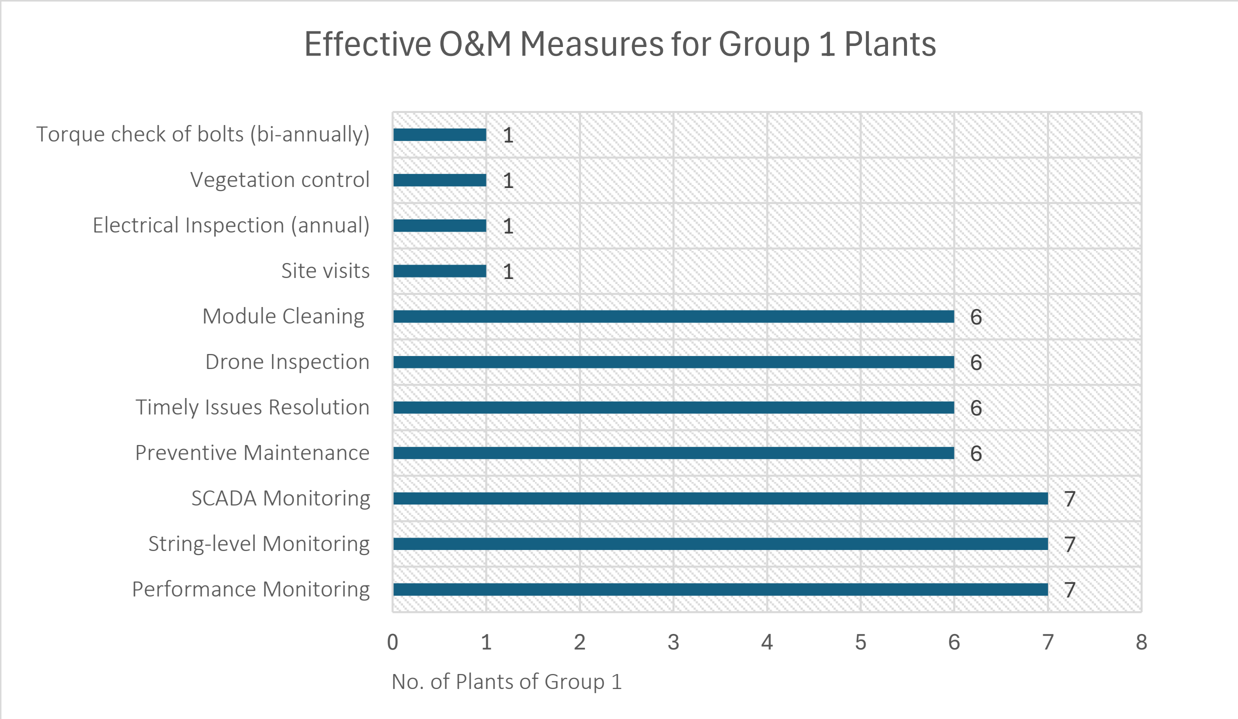

Figure 22: Effective O&M practices for Group 1 plants

Regarding potential improvement suggestions, enhanced staff training and increased automation were the most frequently mentioned measures, each highlighted by 7 plants. These responses indicate a strong interest in strengthening workforce capabilities and in leveraging technological advancements to improve operational efficiency.

In addition, 4 plants emphasized the need for better spare-parts planning and improved logistics, showing that spare-parts management is an ongoing process that requires continuous optimization to support timely maintenance activities.

Finally, enhancements to SCADA monitoring and improvements to O&M documentation were identified as priorities by 2 plants each, while the remaining suggestions were raised only once across the sample.

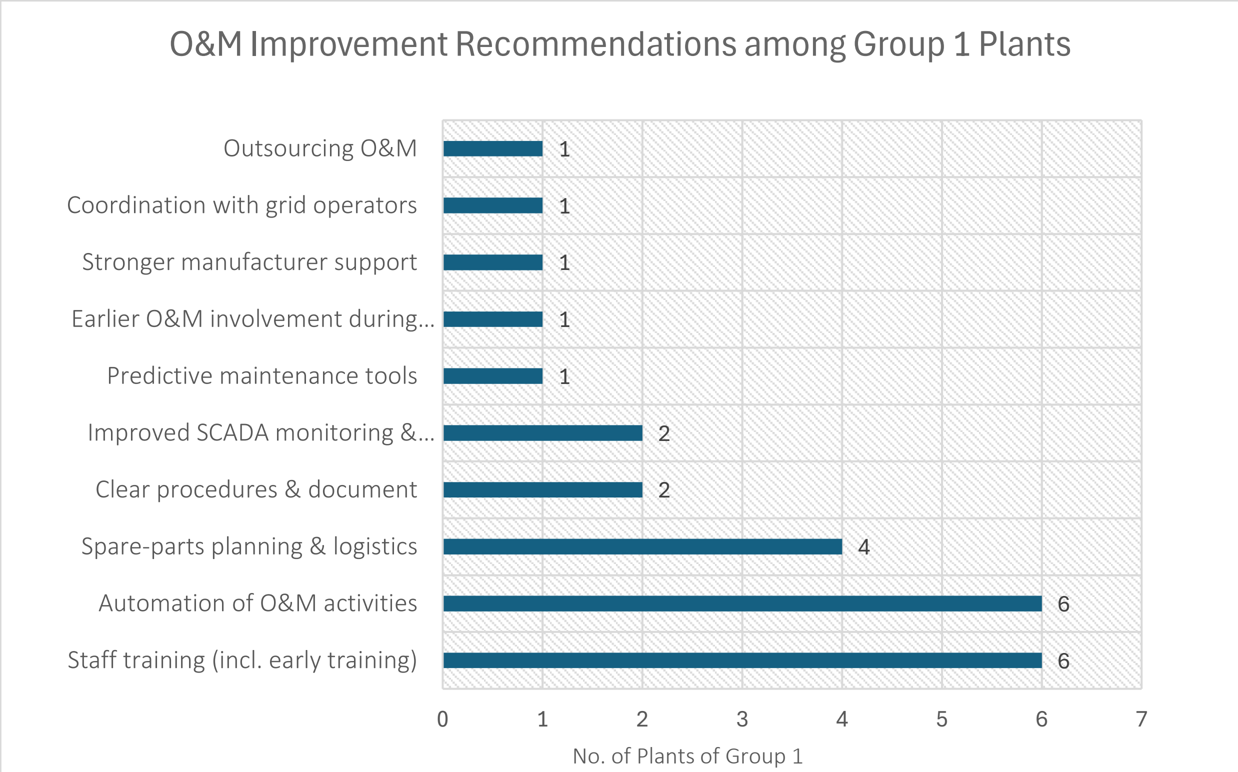

Figure 23: O&M Improvement Recommendations among Group 1 plants

3.4.5 O&M Challenges and Costs

In terms of the annual O&M cost per MVA_{AC}, the results are presented in Figure 24 for the four plant rating ranges. In general, as plant size increases, the cost per MVA_{AC} decreases, benefiting from economies of scale. It should be noted that the third rating range (3.01–4.0 MVA_{AC}) includes only two plants and, therefore, cannot provide statistically reliable results.

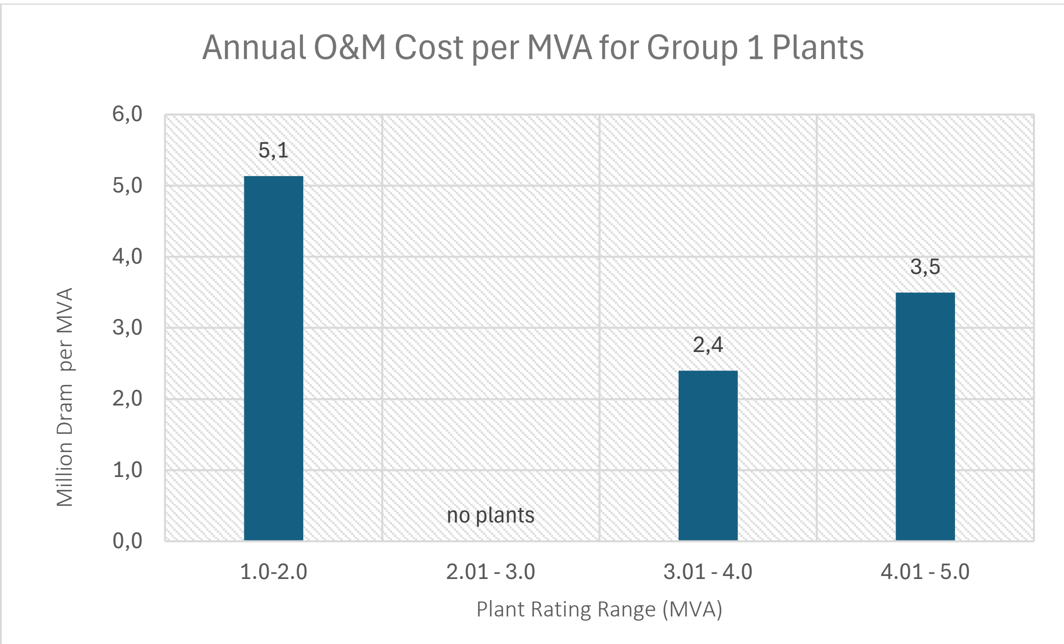

Figure 24: Annual O&M costs in AMD per installed MVA_{AC} among size tiers for Group 1 plants

Based on the responses received, all plants, except for one that reported higher expenditures, indicated that their O&M costs were in line with expectations. This suggests that cost planning and estimation were performed adequately during project development.

The difficulties encountered in operating and maintaining the plants are shown in Figure 25. The most significant challenge is the limited availability of qualified technicians in the country. This is followed by concerns related to spare-parts availability and site access constraints, both of which can delay maintenance activities and increase response times. Equipment reliability was also mentioned as a challenge, highlighting the importance of selecting appropriate vendors and ensuring that sufficient warranties and service agreements are in place.

In addition, two plants reported issues associated with the quality of the national electrical grid, two plants identified no major challenges, and one plant pointed to adverse environmental conditions as a factor complicating plant operation.

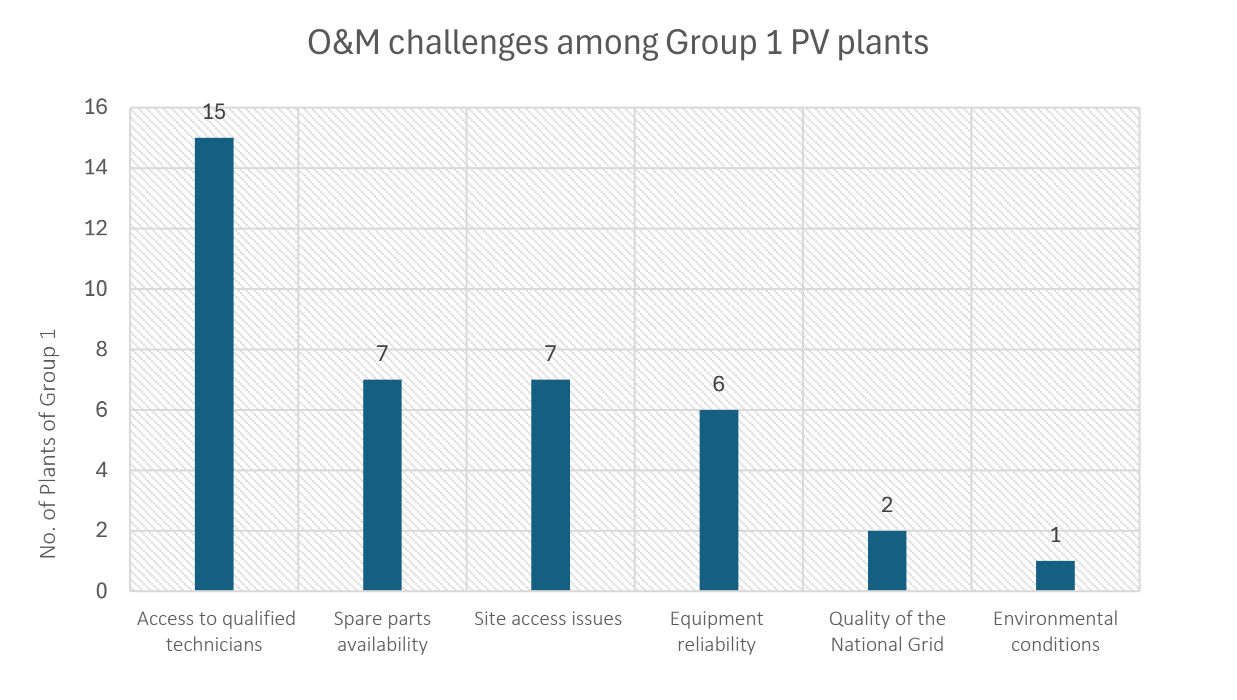

Figure 25: O&M challenges among Group 1 PV plants

3.5 Grid Interconnection

3.5.1 Grid Availability

The survey indicates that grid-related downtime is a common issue, with 26 plants (81%) reporting downtime and only 6 plants (19%) remaining unaffected.

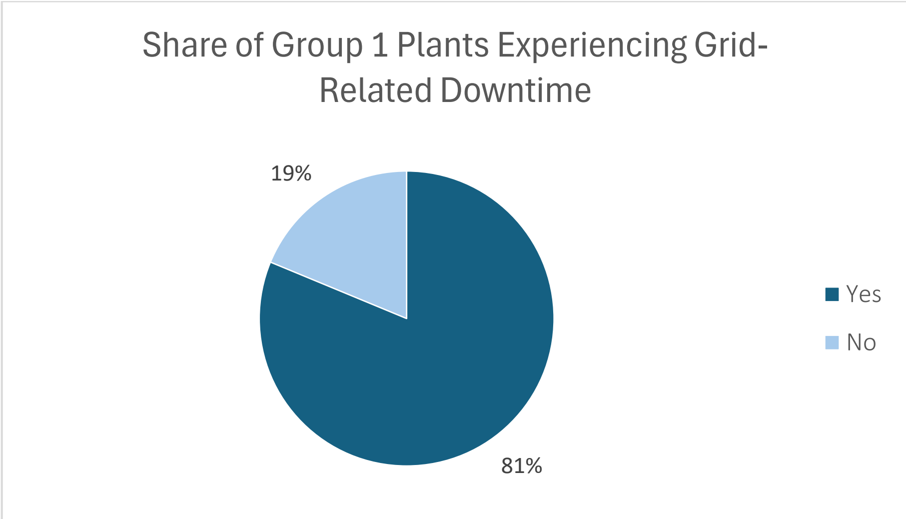

Figure 26: Share of Group 1 plants experiencing grid-related downtime

However, for plants experiencing downtime, the annual duration ranges between 8 and 32 hours for 50% of the plants, with a median value of 26 hours. Even in the worst-case scenario, with an unavailability of 55 hours, the annual availability remains at 99.37%, which is consistent with European standards. Overall, while the frequency of grid downtime may initially appear elevated, the resulting grid availability is sufficiently high and aligned with European standards.

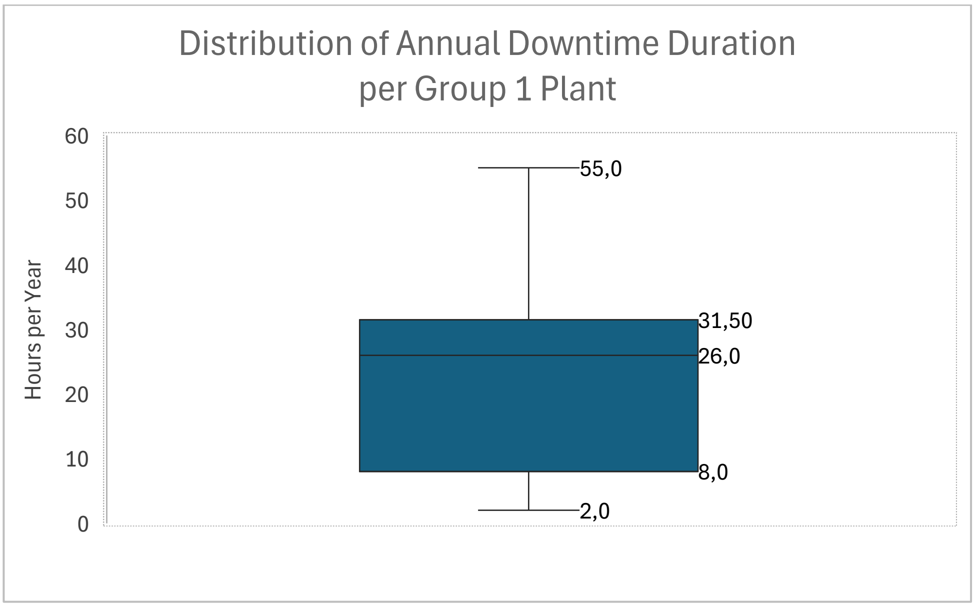

Figure 27: Distribution of annual downtime duration per Group 1 plants

In essence, although the frequency of the grid downtime with a first look seems high, the grid availability is sufficiently high an in line with the European standards.

3.5.2 Curtailment

Grid curtailment was reported in one out of four plants (8 cases in total) participating in the survey.

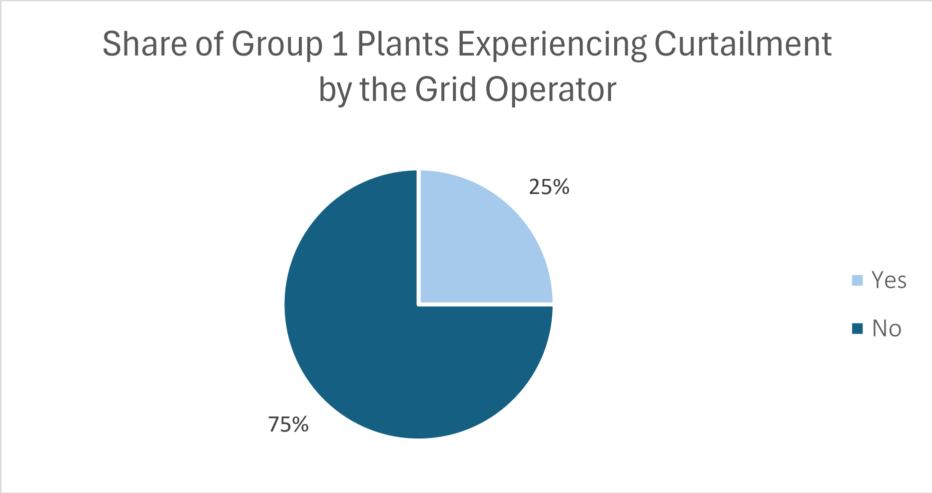

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Figure 28: Share of Group 1 plants experiencing curtailment by the grid operator

Where it occurred, the impact on annual production was limited, with an average curtailed energy of 0.54% and a maximum of 1.23%, indicating a generally minor effect on overall energy yield.

The reasons behind curtailment are presented in Table 3 (several ones could be reported per plant and per curtailment incidence). Planned maintenance is the most common cause of curtailment, followed by unplanned grid outages and general grid congestion or a weak grid. On the other side, congestion of the grid during renewables peak production hours was reported only three times.

Overall, curtailment incidents were limited and had only a minor impact in terms of lost (i.e., curtailed) electricity. Nevertheless, when curtailment did occur, it was primarily driven by the condition of the Armenian grid rather than by excessive integration of renewables beyond the grid's capacity. This indicates that there is still room for further renewable energy integration.

The parallel integration of Battery Energy Storage Systems (BESS) can help balance supply and demand, mitigate curtailment, and stabilize grid operations by storing excess solar generation and releasing it during periods of higher demand or grid constraints. In this way, storage systems support smoother renewable integration and enhance the overall resilience of the power system.

	Reason for Curtailment	No. of Plants
General Grid Challenges	Planned grid maintenance	7
	Unplanned grid outages	3
	General grid congestion / weak local grid	3

	Reason for Curtailment	No. of Plants
RE Integration	Grid congestion during renewables peak production hours	3

Table 3: Reasons for curtailment among Group 1 PV plants

3.5.3 Interconnection Equipment

In terms of interconnection equipment, none of the plants experienced problems. Nevertheless, two of the plants (6.2%) had power quality issues, with the one facing harmonics and voltage fluctuations, while the other experienced grid outages lasting one to two hours per month.

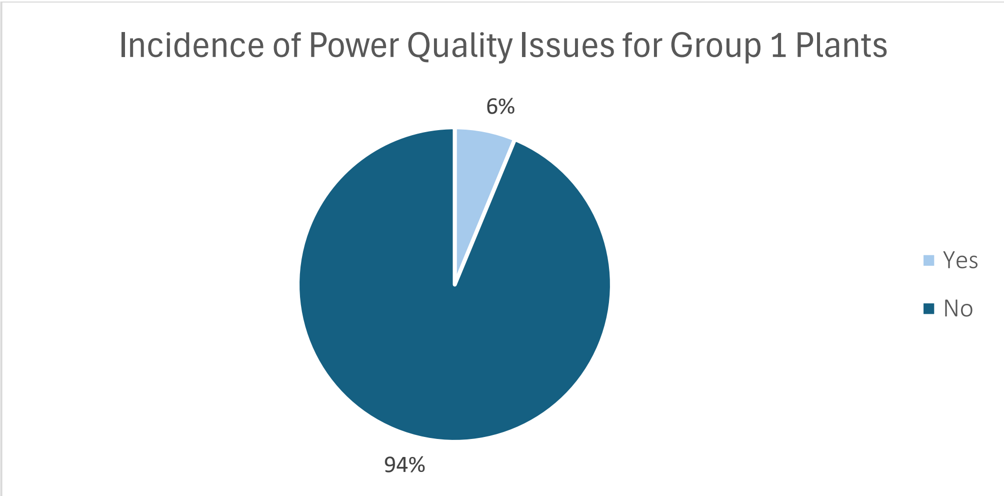


Figure 29: Incidence of power quality issues for Group 1 plants

3.6 Environmental Issues

Among the 32 plants participating in the survey, only one reported environmental issues, specifically soil erosion, which required the addition of large gravel to mitigate and slow down the erosion process. Overall, non-occurrence of environmental problems indicates proper environmental assessment prior project construction.

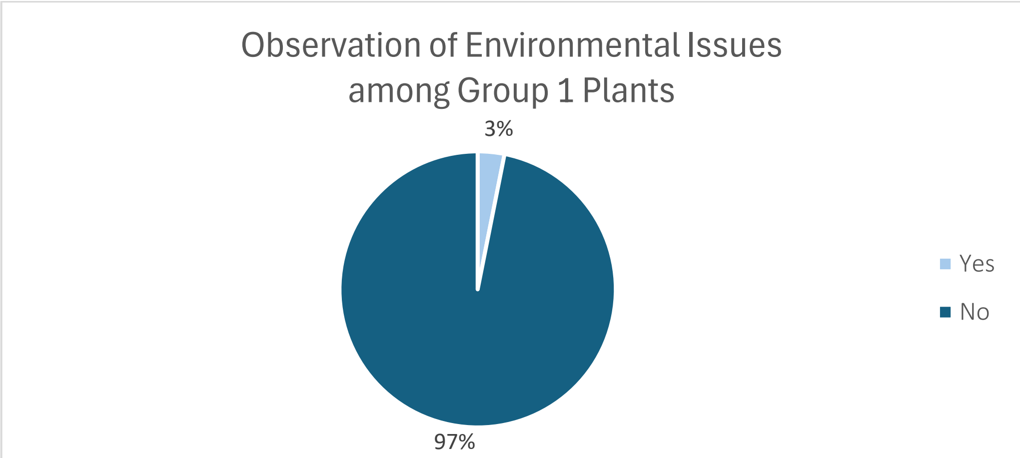


Figure 30: Observation of environmental issues among Group 1 Plants

3.7 Health and Safety

In terms of HSE, the situation appears very positive, as no accidents or incidents were reported across the plants as presented in Figure 31.

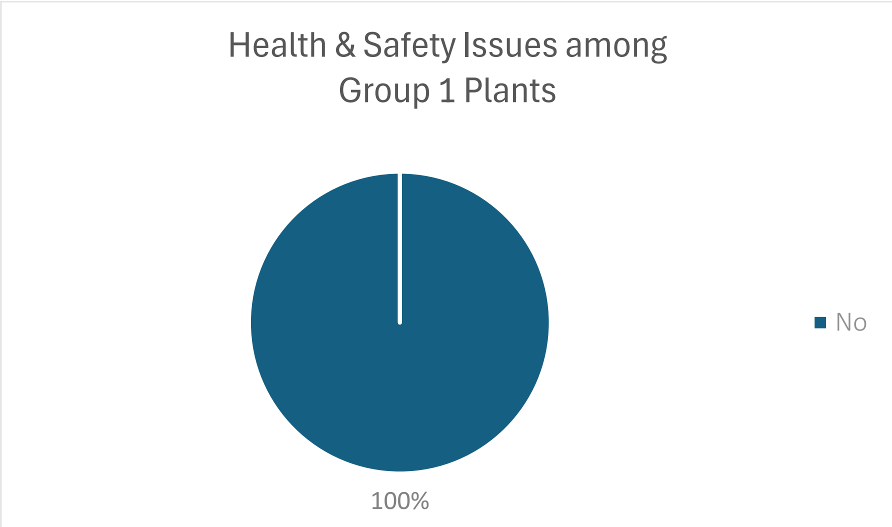


Figure 31: Observation of health & safety issues among Group 1 Plants

Moreover, all facilities have a formal Environmental, Health and Safety plan in place and have not encountered any difficulties with implementing safety procedures.

3.8 Relationship with Local Communities

The relationship with the local community is overwhelmingly positive. All respondents reported either a very positive (19 plants) or positive (13 plants) relationship, indicating strong local acceptance and constructive engagement across all surveyed plants. Additionally, there were no complaints from the community about the PV plants.

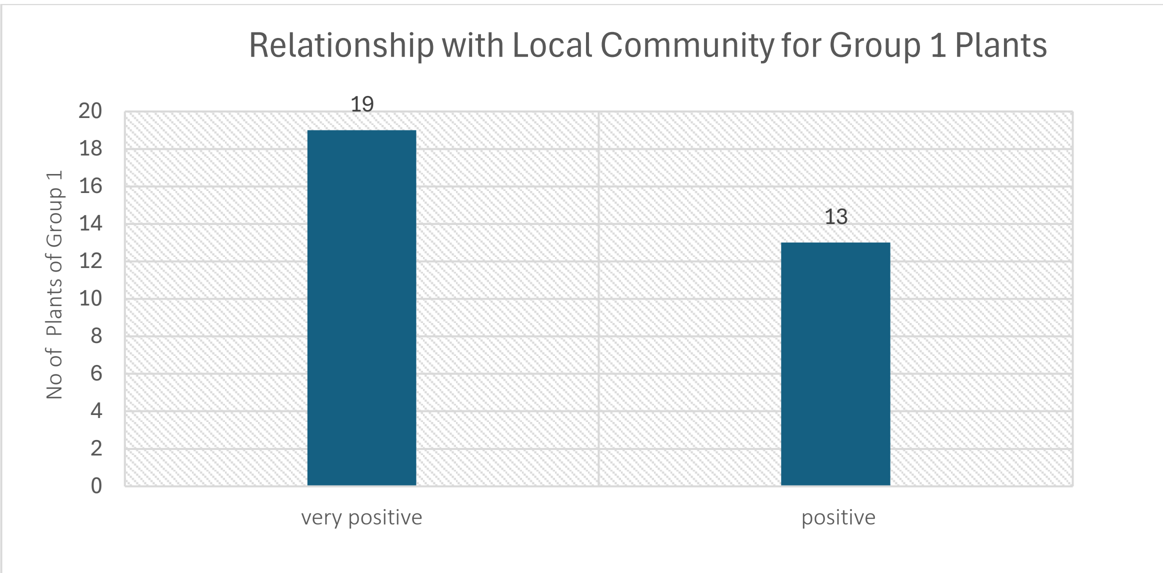


Figure 32: Relationship status with local community for Group 1 plants

Although, as explained above, the relationship with the local community is positive, plant owners generally do not undertake dedicated community benefit activities. Specifically, only 3 plants (9.3%) reported efforts to actively engage or support local communities, either through the construction of new buildings (2 plants) or through a company-level Corporate Social Responsibility (CSR) plan, under which solar panels were provided to a local school (1 plant).

Furthermore, only 37% of the surveyed plants responded that they have a formal grievance management. This shall be expanded to all plants to address and resolve community complaints promptly and fairly.

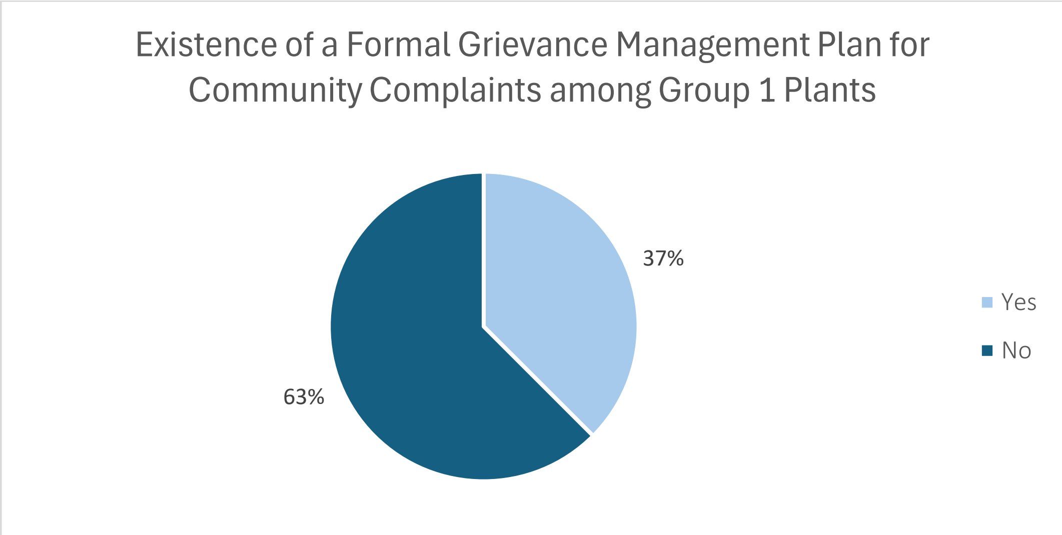


Figure 33: Existence of a formal grievance management plan for Group 1 Plants

3.9 Regulatory Environment

Among the 32 plants in total, only one faced significant regulatory requirements related to the land permit, category classification, grid access as presented in Figure 34. In this case, the permitting process was prolonged. The feedback is hence deemed quite positive, since permitting is pretty often an important bottleneck when building new renewable plants.

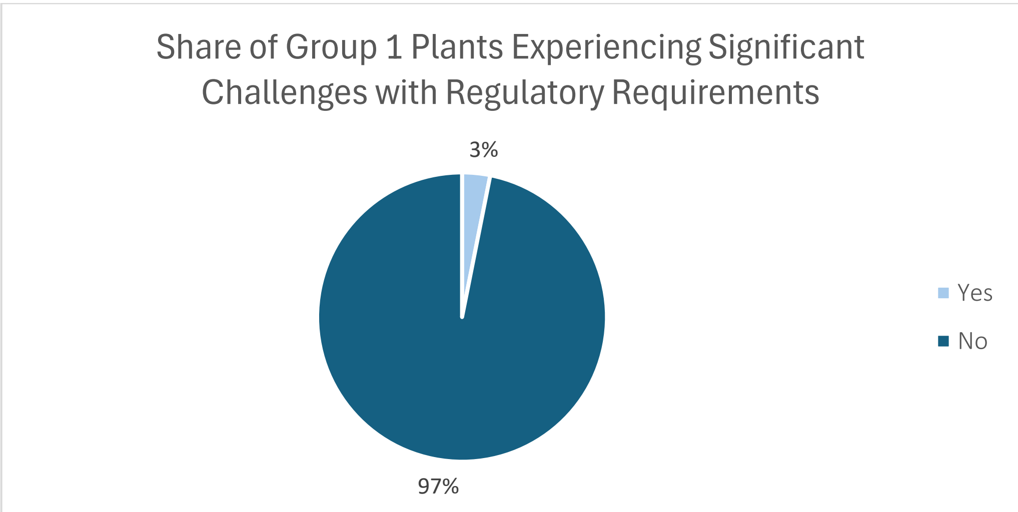


Figure 34: Share of Group 1 plants experiencing significant challenges with regulatory requirements

In addition, when asked whether any regulatory changes introduced after commissioning had affected plant operations, only 3 plants reported experiencing such changes, as outlined in Table 4 below.

Change	Description
▪ No1	▪ Annual tariff review by the Public Services Regulatory Commission (PSRC).
▪ No2	▪ The price was reduced by 10%.
▪ No3	▪ The PSRC has recently introduced curtailment rules for plants benefiting from a guaranteed feed-in tariff. Despite the inclusion of a compensation mechanism, these changes may affect operational practices and revenue predictability.

Table 4: Regulatory changes occurred since commissioning of the PV plants of Group 1

Overall, the experience with the regulatory environment is considered positive, and the suggested adjustments are therefore limited. In fact, eleven (11) plants indicated that no changes are needed.

Among the proposed improvements, the most frequently mentioned were the need for clearer shutdown regulations (6 plants) and a simpler electronic data submission system (6 plants).

Additionally, two (2) plants expressed interest in a centralized permitting support system, while one (1) plant suggested introducing a single-window for all document submissions.

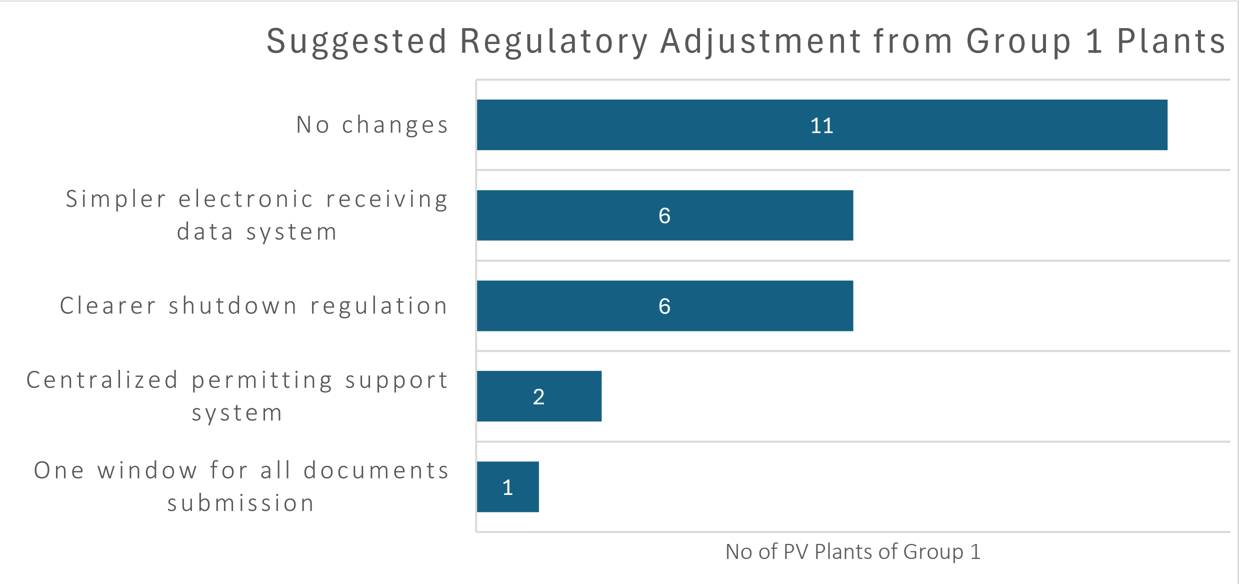


Figure 35: Suggested regulatory requirements from Group 1 plants

3.10 Institutional Support

Overall, institutional support is perceived as moderate across most public institutions, with average scores of 3.2 for the Ministry of Territorial Administration & Infrastructure and the Grid Operator, and 3.8 for the Public Services Regulatory Commission, Local Authorities and the State Urban Development Committee.

In contrast, GAF and Partner Financial Institutions record higher average scores of 5.0 and 4.3 respectively, indicating stronger and more consistent support.

Lastly, to be noted that 4 PV plants (12.5%) declared being fully satisfied (5 out of 5) with the EPC contractor, which was in their case Shtigen.

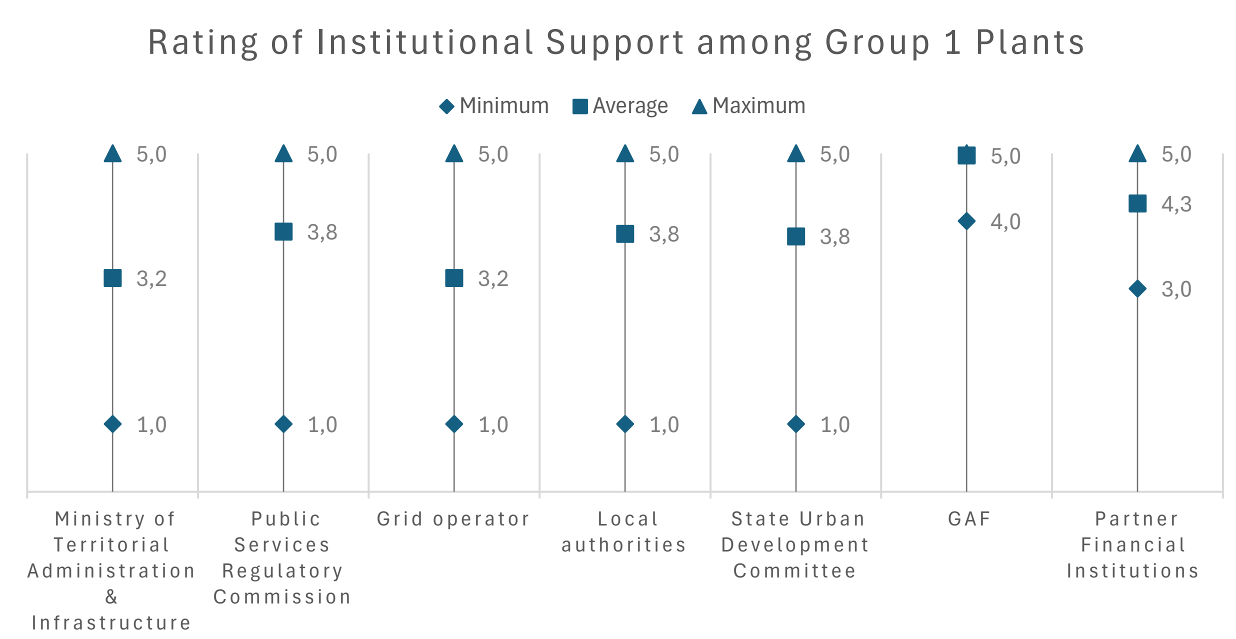


Table 5: Rating of Institutional Support among Group 1 Plants

Most respondents considered the existing institutional framework adequate, with 14 plants indicating that no improvements are required.

Four (4) plants in Group 1 reported delays in response times from the grid operator, while two plants highlighted the need for dedicated training programs to better support owners.

Finally, one (1) respondent emphasized the need for a national BESS program supported by targeted financing mechanisms and the implementation of ancillary service markets.

3.11 Financing

The financial expectations of the PV plant owners were largely met, with 87% of the plants meeting expectations and 3% of the plants even exceeding expectations. In only two cases, the resulting financial outcome was not as expected. For the plant with results significantly below expectations, one factor mentioned was the unavailability of 0.8 kV experts in the country While this is certainly important, it alone cannot explain such poor performance. For the plant with slightly below expectations, the causes were overestimated yield projections, more challenging tracker maintenance, and delayed commissioning by the EPC.

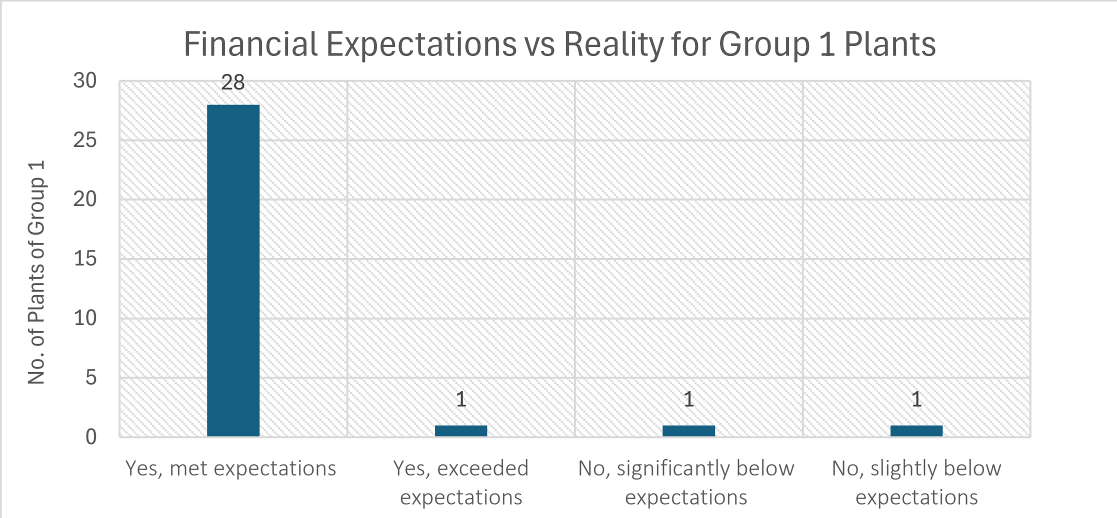


Figure 36: Financial expectations vs reality for Group 1 plants

In terms of experiencing financial challenges, among the plants that had given a reply (only 53% of the participants), bank guarantees and collateral requests were the most common issue (8 cases). Other challenges, such as refinancing difficulties, early loan payments, and reduced income from OHTL construction, were only faced once. Lastly, to be highlighted that 6 plants faced no financial challenges at all in their investment.

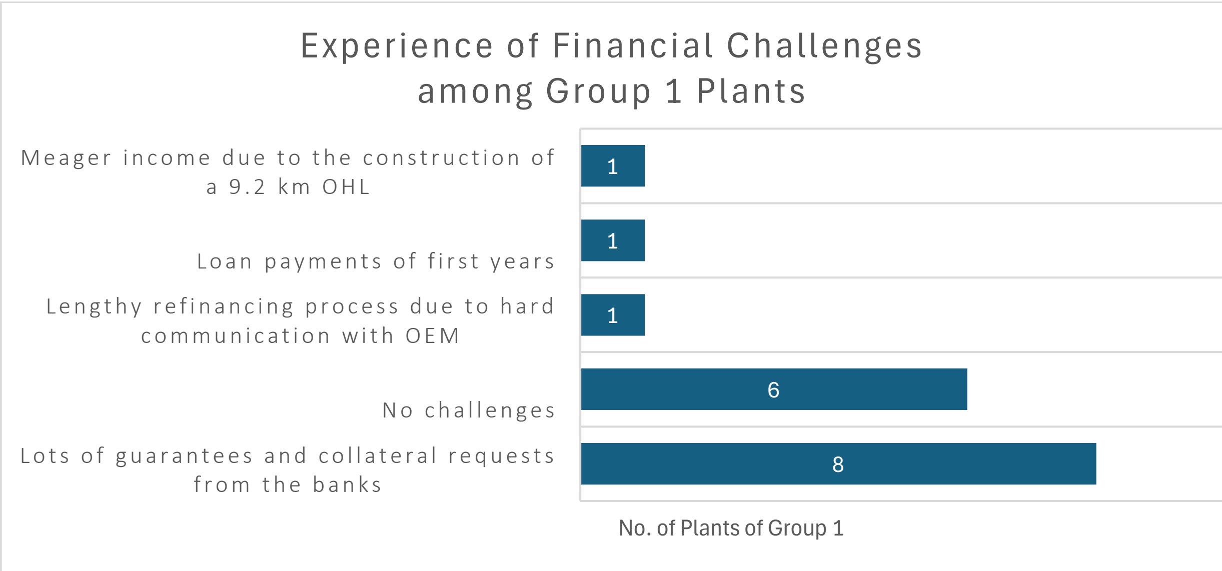


Figure 37: Experience of financial challenges among Group 1 plants

Regarding financing program improvements, the requested modifications from the PV plants that expressed an opinion were relatively straightforward:

- faster decision-making (5 plants), and
- lower loan interest rates (8 plants).

Both aspects can positively influence investment decisions, either by shortening the overall plant development process or by increasing revenues for investors.

Regarding satisfaction with the GAF-RE funding conditions, all plants expressed a positive opinion, with 20% considering that GAF can additionally influence banks toward more moderate interest rates and with a further 10% seeking longer-term reduced rates.

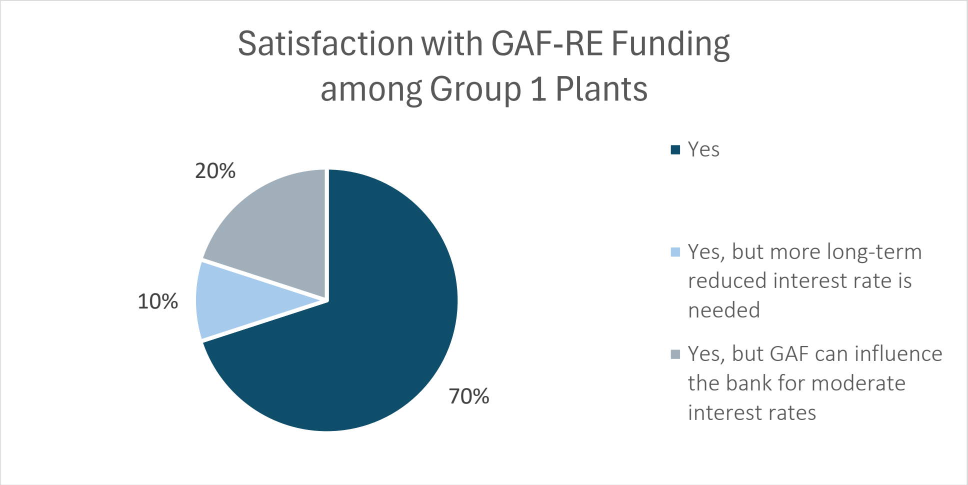


Figure 38: Satisfaction with GAF-RE Funding Scheme among Group 1 Plants

The overall satisfaction is reflected in the willingness to seek future funding from GAF, with 80% of the plants expressing a desire to do so for other renewable energy generation and Battery Energy Storage Systems (BESS) projects. Meanwhile, 10% of the respondents were negative about securing future funding, and another 10% were not ready at this point in time.

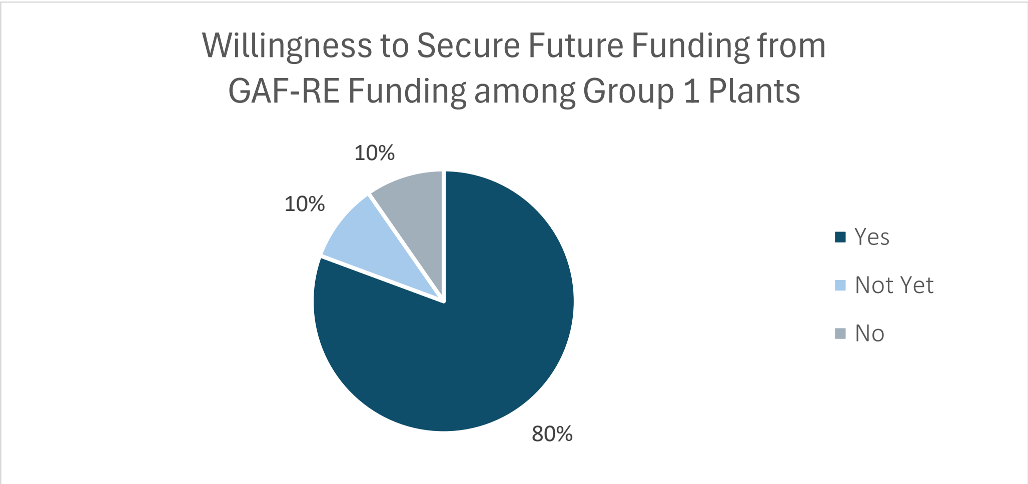


Figure 39: Willingness to secure future funding from GAF-RE Funding among Group 1 plants

3.12 Construction Experience

Regarding construction issues, in half of the cases no problems were identified, which is a rather positive outcome. The most common challenge encountered was the need for extensive earthworks due to poor soil quality (6 plants), while three (3) plants experienced grounding issues. The remaining issues were reported sporadically and included cable management shortcomings, delayed commissioning, and inadequate drainage.

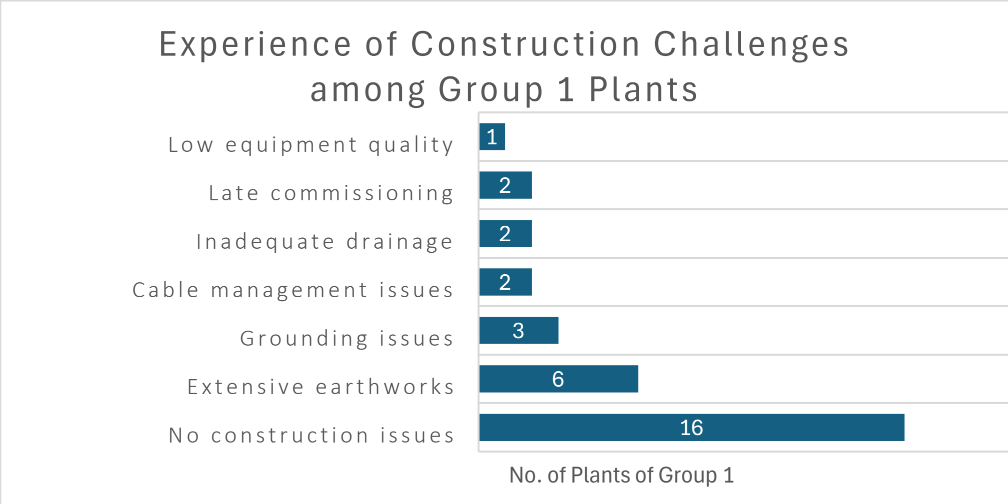


Figure 40: Construction issues among Group 1 Plants

When asked how the construction process can be improved, the focus was mostly on collaboration with institutions. Faster responses by agencies (22%), relaxation of deadlines (6%) and clear interconnection conditions (6%) are the requests of the PV plants. In addition, a better EPC experience was highlighted in 5 cases (16%), while usage of qualifying experts is also needed (6%).

The satisfaction of the PV plants with Fichtner as an Owner's Engineer (OE) is reflected in Figure 41.

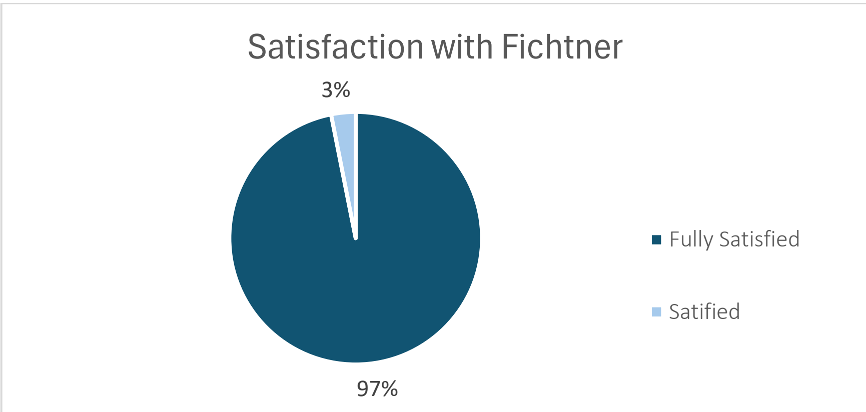


Figure 41: Satisfaction of PV plants with Fichtner as OE

The great satisfaction of the PV plants is also reflected in the below comments with the responses exactly as shared with the questionnaire:

''Fichtner brought significant value to the project through their deep technical expertise, structured approach, and commitment to high-quality results. Their involvement greatly enhanced the overall quality and reliability of project outcomes.

The duration and frequency of site visits were well planned and appropriate for the project's needs. Fichtner's presence on-site ensured thorough assessments and proactive issue resolution.

Communication with Fichtner was excellent throughout the engagement. Their team was consistently responsive, transparent, and proactive in addressing all requests and providing timely updates.''

3.13 Recommendations for PV Sector in Armenia among Respondents

In terms of general recommendations in order to improve PV projects in Armenia, the replies varies among respondents of Group 1 PV plants and are presented in the various categories in Table 6.

Category	Suggestion	Frequency
Grid	Strengthen grid infrastructure incl. OHTLs and substations	16
Permits	Optimize permitting and support mechanisms	4
Design	Follow IEC commission standards	9
	Choose top components	9
	Choose an experienced designer	3
	Use a single EPC contract with clearly defined responsibilities instead of multiple contractors.	1
O&M	Frequent cleaning of modules	6
	Qualified staff	6
Financing	Encourage local and international financing partnerships for PV projects	3
	Lower interest rate for loans	1
	PSRC should introduce commercially viable licenses to encourage battery installations	1

Table 6: General recommendations for the PV sector in Armenia from Group 1 PV plants

Regarding the grid, there were strong complaints for necessary improvement of the infrastructure including both the OHTL and the substations to which the PV plants interconnect to. This suggestion seems logical if someone refers to the grid availability issues as outlined in Section 3.5.1.

Regarding the permitting, an optimization of the whole process and the related support mechanisms is necessary in order to accelerate the procedure and its bottlenecks.

Regarding plant design, the most frequently cited recommendation was to follow IEC standards during commissioning, followed by the selection of an experienced designer. Concerning the EPC approach, one respondent highlighted that appointing a single EPC contractor is more effective than adopting a multi-EPC strategy.

Lastly, regarding financing, plant operators would like to explore local and international partnerships, seek lower interest rates as mentioned previously, and would like to see licenses made available for BESS projects.

3.14 Follow-up Engagement

In total, 97% of the respondents were willing to share documentation in order to support the survey. This includes mainly monthly energy production data and in some cases maintenance logs and O&M reports.

In terms of conducting a brief site visit to verify certain aspects of the plant, the vast majority of plant owners (87%), were positive indicating a collaborative and improvement-oriented spirit.

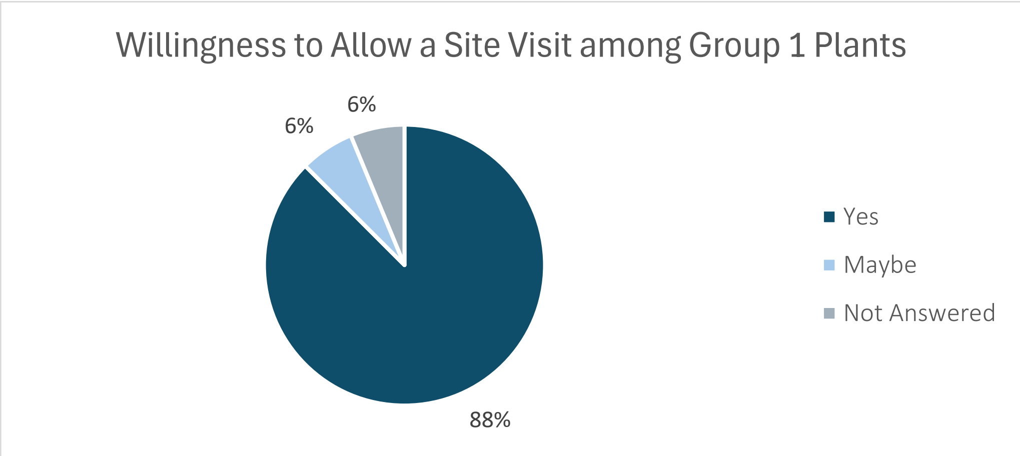


Figure 42: Willingness to allow a site visit among Group 1 plants

4 Analysis of Group 2 - Small Scale PV Plants

4.1 Sample Overview of Group 2

4.1.1 Plants Installed DC Capacity

The survey investigated 45 plant with the DC installed capacity values ranging from 3.3 to 636 kW_{DC}. The distribution of the plants into the different size tiers is as follows:

- The 1-212 kW tier comprises the vast majority of the plants, namely 40 plants.
- The 213-424 kW tier includes only 1 plant.
- The 425-636 kW tier include 3 plants.

Overall, the data are clustered around the first tier with the rest of the cases actually being outliers. To be noted that for one case, the installed capacity was not disclosed.

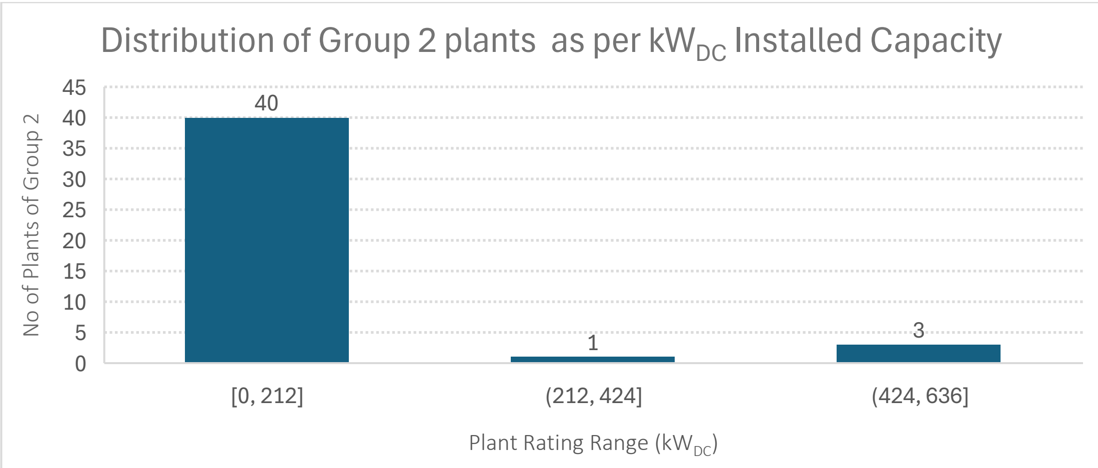


Figure 43: Distribution of Group 2 plants as per kW_{DC} Installed Capacity

4.1.2 Type of Systems and Main Business Category

The system type of these plants are presented in Figure 44. Rooftop systems clearly dominate (38 cases), indicating a preference for space-efficient installations. Ground-mounted systems are limited (5), and hybrid systems are rare (2), suggesting few mixed configurations.

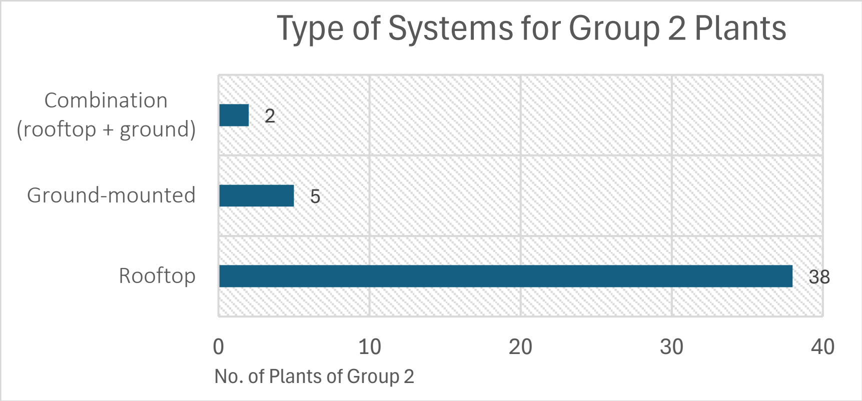


Figure 44: Type of systems for Group 2 plants

These PV installations are primarily concentrated in manufacturing/production (19) and family houses (13). Retail/shops and services follow, with four (4) and three (3) plants, respectively.

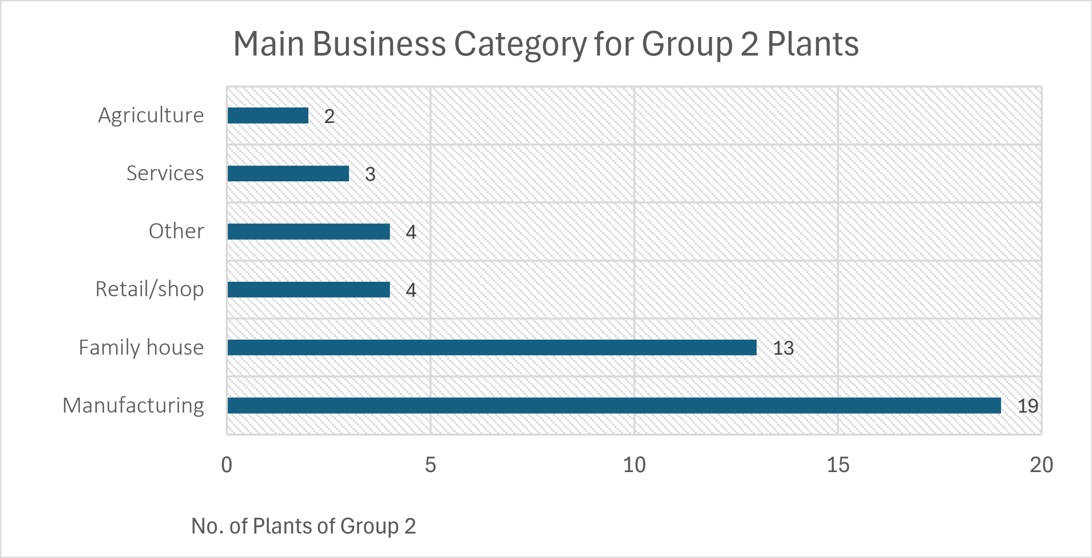


Figure 45: Main business category for Group 2 plants

4.2 Focus on Rooftop Systems

Looking closer to the roof mounted plants only, the building types on which the modules were mounted are summarized in Figure 46. The modules are mainly installed on Commercial/industrial buildings (21) and family houses (13), together accounting for the majority of cases. Agricultural buildings (3) follow, while cinema , separate roof and mixed use are marginal, with only single representation each.

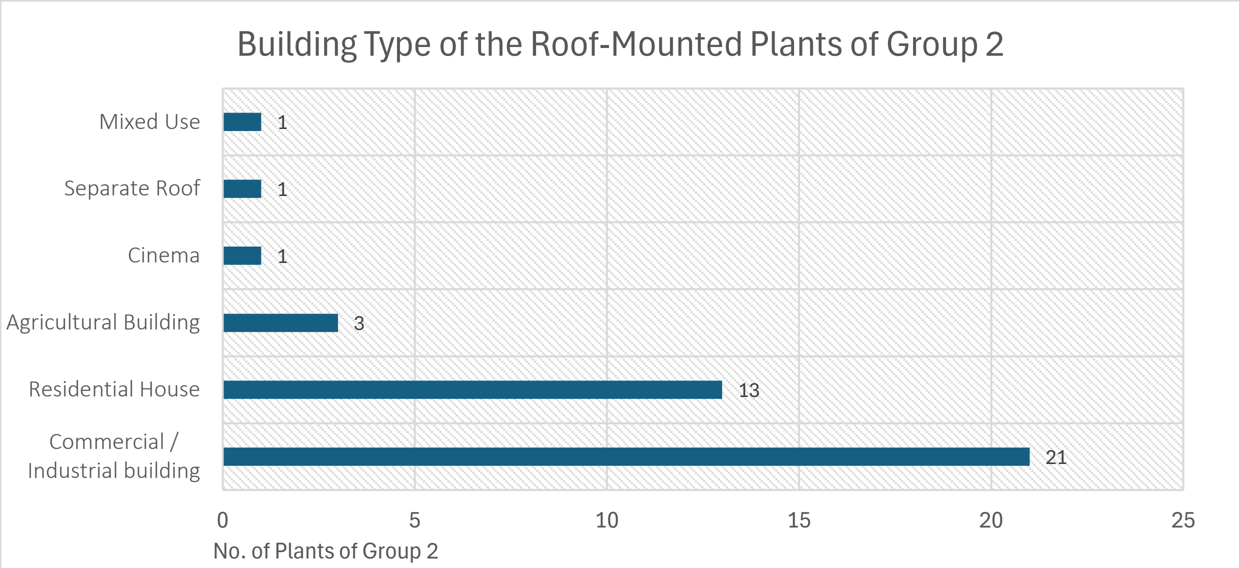


Figure 46: Building type of the roof-mounted plants of Group 2

4.2.1 Roof Inspection and Condition

Most installations were preceded by a professional structural inspection (75%). However, about one quarter relied solely on a visual check by the installer (22%), which poses structural risk since it cannot fully identify all problems.

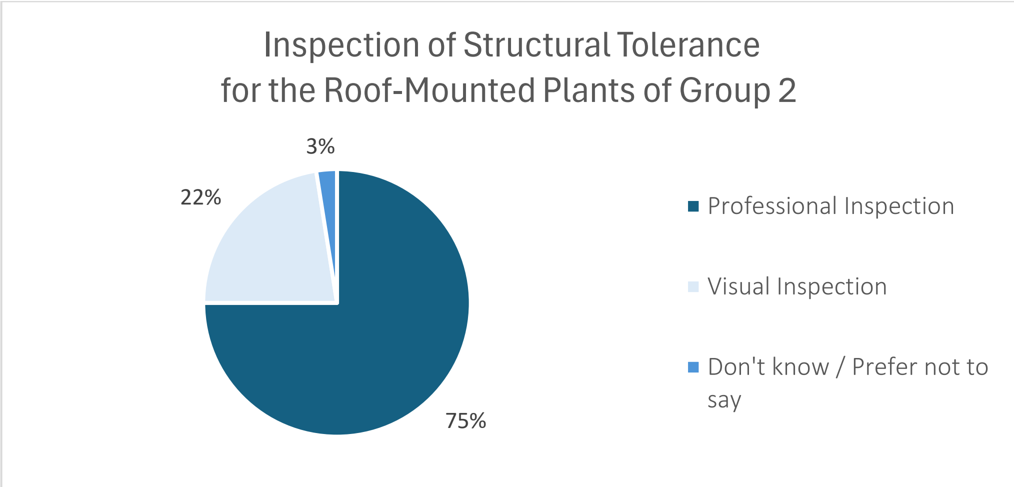


Figure 47: Inspection of Structural Tolerance for the roof-mounted plants of Group 2

Based on the inspections conducted, the majority of roofs were reported to be in good condition at the time of installation (60%), while a substantial share had new or recently repaired roofs (37%), indicating favourable pre-installation conditions.

Nevertheless, as explained above, a professional inspection was not carried out in all cases, potentially concealing underlying issues. The recommended engineering practice is to conduct a roof inspection that includes structural calculations—such as estimating dead loads, wind loads, and snow loads—reviewing the building's structural drawings, and comparing the calculated loads with the requirements of the applicable building codes.

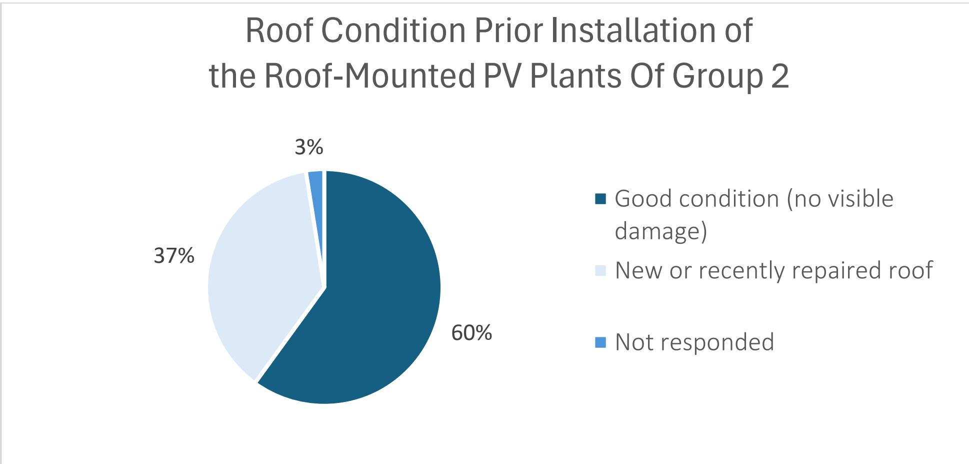


Figure 48: Roof condition prior Installation of the roof-mounted PV Plants of Group 2

4.2.2 Installation

Most PV systems were installed 0.5–1 m from the roof edge (19) or more than 1 m away (17), suggesting general compliance with setback practices. Only a small number were placed closer than 0.5 m (4), which may increase risks during installation and maintenance.

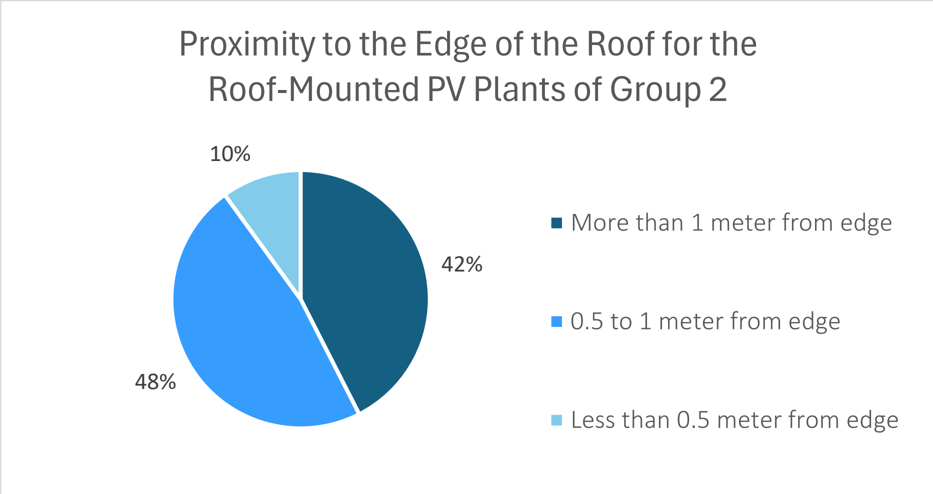


Figure 49: Proximity to the edge of the roof for the roof-mounted PV Plants of Group 2

Regarding installation issues for these systems (Figure 50), the vast majority reported no problems. Only four cases experienced roof leaks near mounting points, which could potentially lead to corrosion and stability issues.

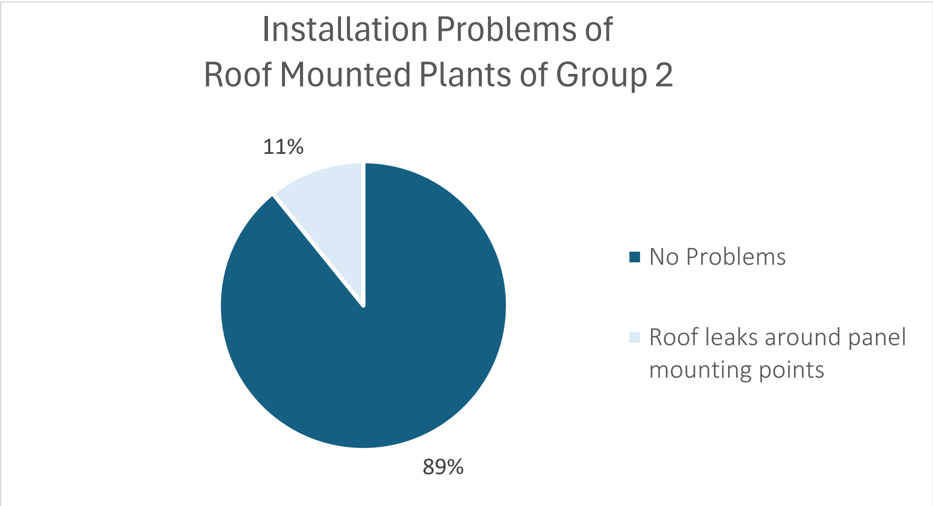


Figure 50: Installation problems of roof-mounted plant of Group 2

4.3 Installation of PV Systems

4.3.1 Installation Companies

Regarding installation companies, a wide range of options (25 in total for the survey) seems to be available in the Armenian market. Among them, Shtigen LLC and Ecoville LLC lead with 5 appearances each, followed by Solaron LLC and Ital Solar LLC with 3 each. Overall, it seems that there are several options for installation companies in Armenia, enabling potentially competitive pricing. Of course, care must always be taken to ensure that the quality of services remains high.

Company	Number of Occurrences	Company	Number of Occurrences
Shtigen LLC	5	IT Park Residential Complex LLC	1
Ecoville LLC	5	Rubinar LLC	1
Solaron LLC	3	Redinet CJSC	1
Ital Solar LLC	3	DV Invest JV LLC	1
Arpisolar LLC	2	Renewable Caucasus Corporation LLC	1
Profpanel LLC	2	Solar Home Consulting Service	1
Solar Holding LLC	2	Solar Tech Energy LLC	1
Solar Home Consulting Service LLC	2	Noy Energy LLC	1
Power Energy LLC	2	Sun Provider LLC	1
Energy Lubs LLC	1	Renewable LLC	1
Volta - U LLC	1	Arpi Solar LLC	1
Renewable Caucasus Coorporation	1	Noy Holding LLC	1
Ray Energy LLC	1		

Table 7: Installation companies of the Group 2 PV plants

4.3.2 Installation Satisfaction and Performance

Overall, the performance of the installation companies was very positive with 93% of plants reported being at least satisfied with the installation, including 51% that were very satisfied. Furthermore, 5% were neutral, while only 2% were very dissatisfied. In the dissatisfied cases, installation was completed two months after loan approval and the plant operated at around 50% capacity for five months due to technical issues. Hence, annual expected production was not achieved.

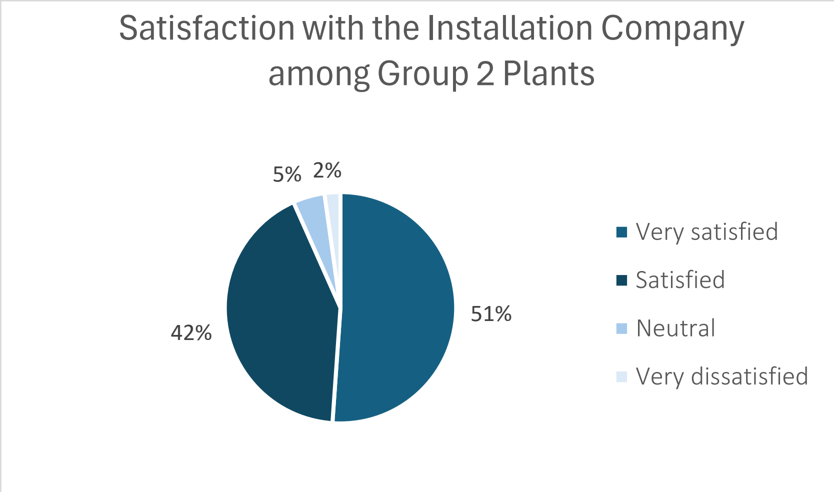


Figure 51: Satisfaction with the selected installation company among Group 2 plants

The installation process was largely smooth, with most respondents reporting no problems (35) or no significant problems (8). Only two of the plants faced issued, with one having difficulties with the inverter installation and the other with cable management, indicating an overall good installation quality.

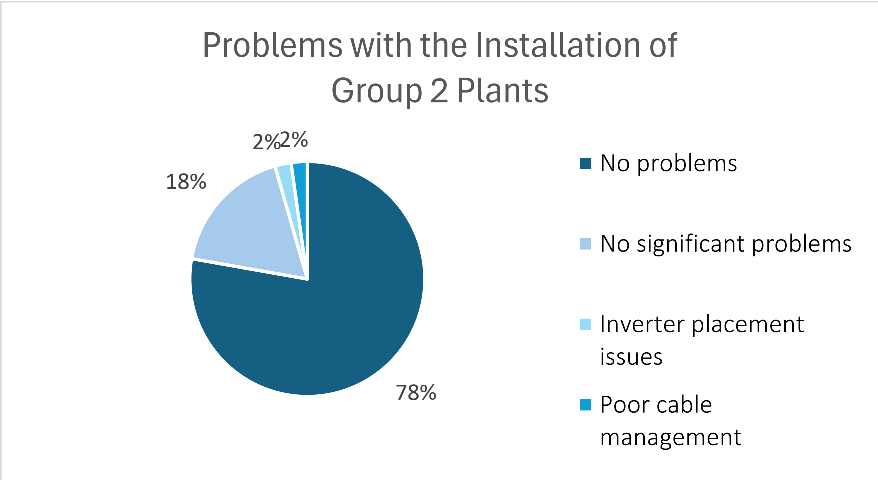


Figure 52: Problems with the installation of Group 2 Plants

4.3.3 Company Selection Criteria

When selecting the installation company, the most important criteria as highlighted by the PV plants are presented in Figure 53.

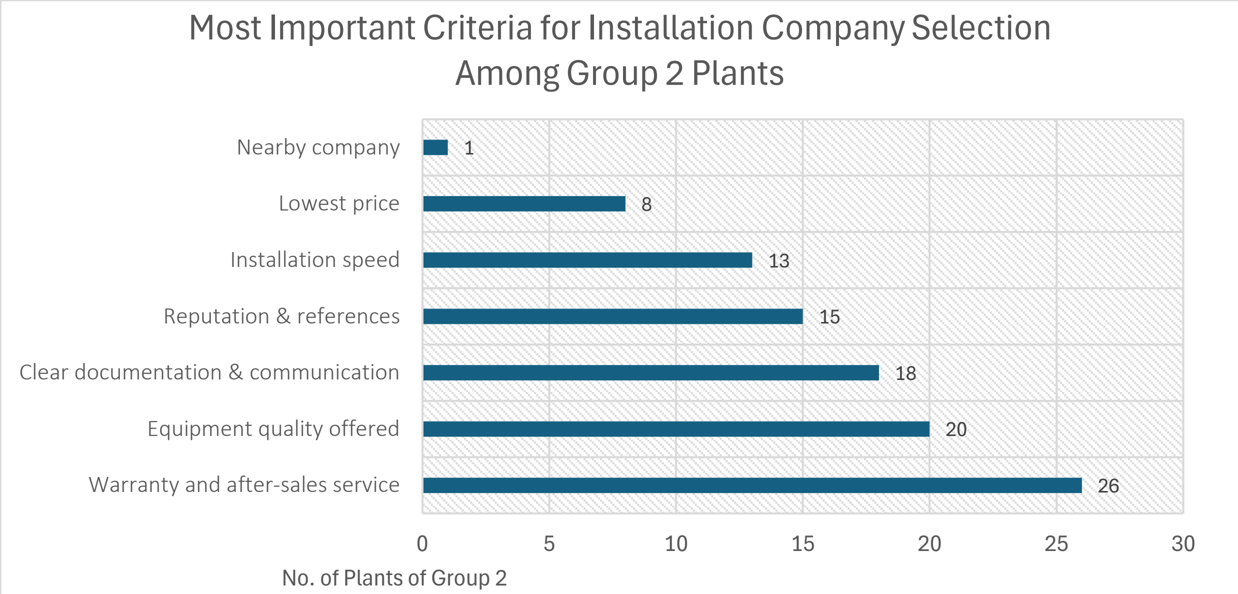


Figure 53: Most Important Criteria for Installation Company Selection Among Group 2 Plants

The results indicate that warranty and after-sales service are the most frequently considered criteria, appearing in over half of the cases. The quality of the equipment offered is also highly valued, while clear documentation and effective communication rank prominently, underscoring (highlighting) the importance of reliability and transparency in project execution.

When selecting an installation company, respondents also considered the company's reputation and the proposed installation timeline (or speed of execution). In contrast, a lower price was given less priority, suggesting a stronger emphasis on long-term value and service quality rather than immediate cost savings.

4.3.4 Produced Documentation

System design/layout drawings are the most commonly produced documents, available in 69% of cases, likely due to the necessity for regulatory approval. A similar trend is observed for electrical single-line diagrams, which were available in 60% of installations.

Equipment manuals and warranties were supplied in 64% of cases whereas, operating instructions (49%), maintenance recommendations (47%), and emergency contact information (47%) were delivered in roughly half of the cases. Nonetheless, to promote and ensure the safe operation of the plants—especially here that the use is domestic or commercial from inexperienced users—it is essential that all plant owners receive comprehensive documentation, including installation & operation instruction manuals.

Type of documentation	Number of appearances	Type of documentation	Number of appearances
System design/layout drawing	31	Installation/commissioning reports	8
Equipment manuals and warranties	29	Detailed system design drawings	7
Electrical connection single-line diagram	27	Grid connection documentation	7
Operating instructions	22	O&M manual and recommendations	6
Maintenance recommendations	21	As-built drawings	5
Emergency contact information	21	Performance guarantee documentation	5
Equipment datasheets and specifications	8	Electrical single-line diagrams	4
Equipment warranties and guarantees	8	Very little or no documentation	4

Table 8: Documentation received after installation of PV system for Group 2 plants

4.4 Energy Production

4.4.1 Monitoring

All PV plants monitor their energy production. Most owners (64%) do so regularly, typically on a weekly basis, while 25% check production occasionally, usually monthly. Only 11% monitor energy production on a daily basis. Hence, there is room for improvement and daily monitoring of the energy production in order to identify any issue early on and act promptly.

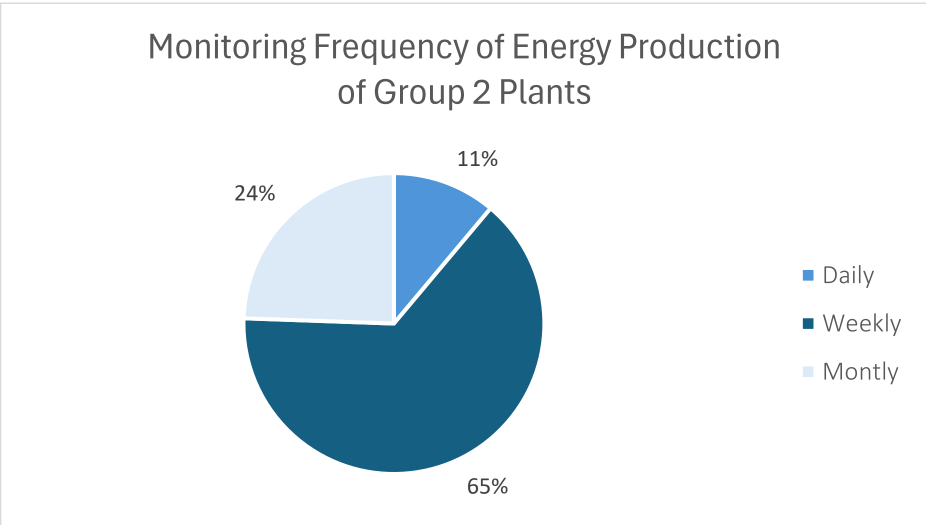


Figure 54: Monitoring frequency of energy production of Group 2 plants

Monitoring is clearly dominated by mobile applications, with 96% of systems using a mobile app.

The second most common method is the inverter display (13 plants), followed by the electricity meter (10 plants). Furthermore, three (3) plants use a web platform, whereas only one plant relies on an external third-party calculation.

Overall, it is encouraging that there is a clear tendency toward user-friendly monitoring, either through a mobile app or the inverter display, as these provide the quickest way to track production on a daily basis. For systems of such small scale, these methods are also the simplest and most intuitive for domestic or commercial users. In any case, proper training remains necessary to ensure the correct interpretation of the data.

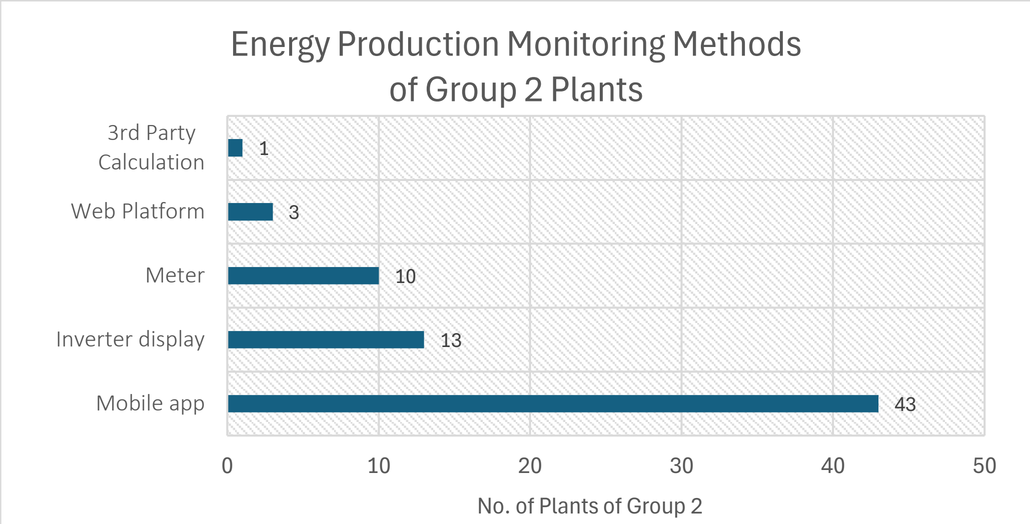


Figure 55: Energy production monitoring methods for group 2 plants

4.4.2 Performance

The overall system performance is in general satisfactory. Most systems perform in line with expectations, with 33 respondents reporting energy production as expected or better. Nonetheless, 10 systems produce somewhat less than expected, while only one reports significantly underperforming. Lastly, one single plant indicated that it is too early to assess its performance, as the facility was operational since 7 months prior to the survey.

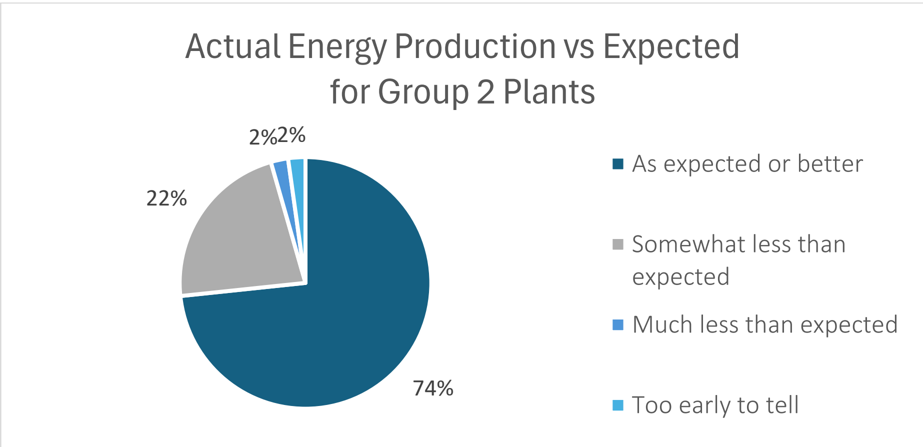


Figure 56: Actual energy production vs expected for Group 2 plants

In terms of performance issues, the feedback is largely positive, with 41 plants reporting no issues and only four (4) experiencing problems.

These were for the reported instances as follows:

- two (2) plants with dirty panels leading to lower energy production (this can be typically up to a 5% energy production loss).
- one (1) plant operated at 50% capacity for an extended time period without the reasoning and further details being given.
- one (1) plant faced multiple simultaneous issues, including:
  - Sudden significant drop in production
  - Complete system shutdowns
  - Production losses due to shading
  - Communication/monitoring system failures

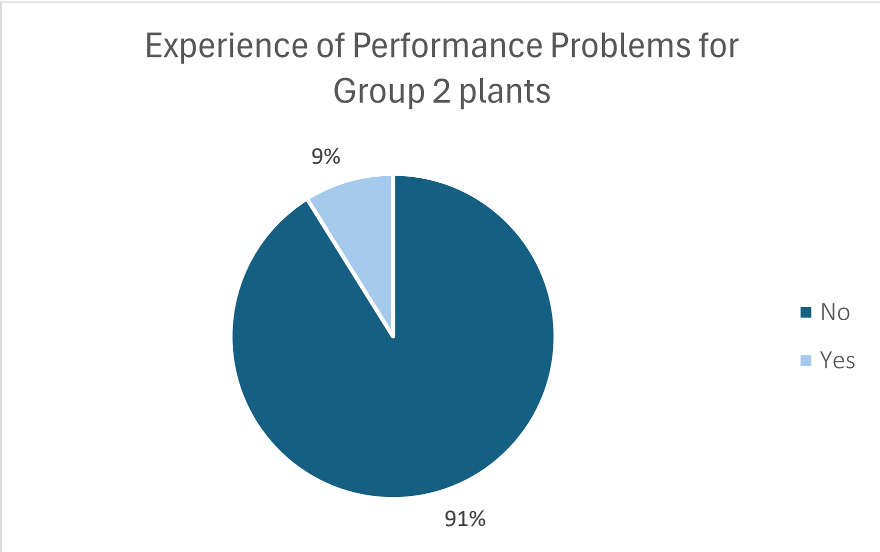


Figure 57: Experience of performance issues for group 2 plants

4.5 Component Failures

4.5.1 PV Modules

Most PV modules appeared to be in good condition (35 cases). However, several plants reported that no inspection had been carried out (6 cases), which introduces uncertainty and is definitely not good engineering practice; this needs to be improved. Lastly, one case showed heavily soiled or covered panels, an issue that can be easily resolved with proper and regular cleaning.

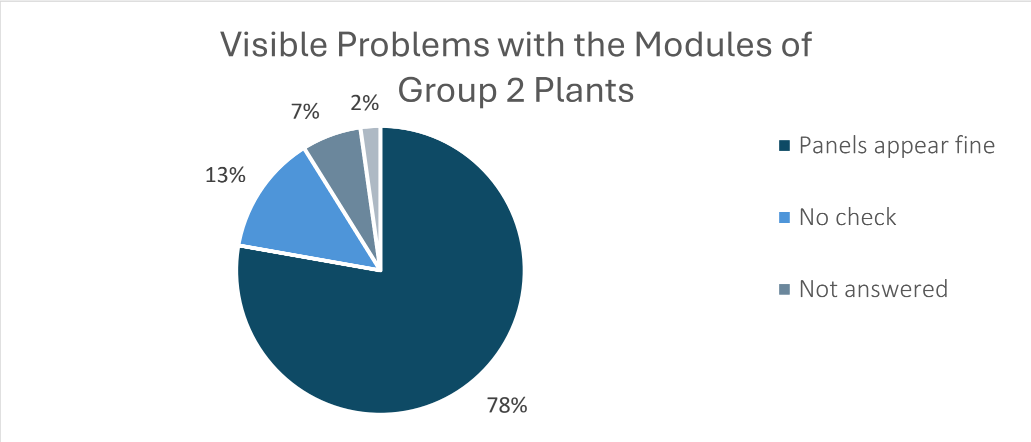


Figure 58: Visible problems with the PV modules of Group 2 plants

4.5.2 Inverters

Regarding the PV plant inverters, the vast majority of cases reported no issues. Only four (4) cases experienced problems, and among these, only one plant provided further details, indicating that the issue was related to communication failures.

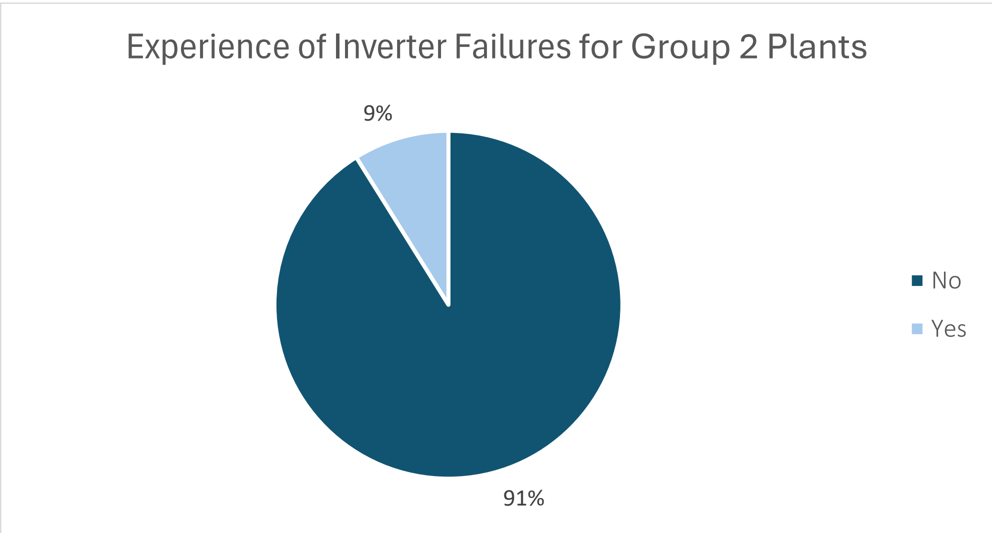


Figure 59: Experience of inverter failures for Group 2 plants

4.5.3 Mounting Structure

Aluminium, being a lightweight and corrosion-resistant solution, is used in 69% of the cases (39 plants). Galvanized steel follows with 9% (4 plants), while in 11% of the cases (5 plants) the owners were not aware of the material. Another 11% (5 plants), which were all rooftop installations, used either painted or powder-coated steel. This choice is generally not considered good engineering practice for rooftop PV mounting structures. For such applications, industry best practice is to use aluminium profiles or hot-dip galvanized (HDG) steel components, as both offer proven long-term durability under outdoor exposure. Aluminium is widely preferred for rooftops because it is lightweight, naturally corrosion-resistant, and easy to handle on buildings with limited load capacity. HDG steel is also acceptable, but it is heavier and therefore less common on roofs. In contrast, painted or powder-coated steel provides only surface-level protection that can be easily damaged during transport or installation. Once the coating is compromised, corrosion begins quickly, which shortens the service life of the mounting system and increases maintenance requirements. By comparison, aluminium remains corrosion-resistant even when scratched, and HDG steel offers sacrificial zinc protection that continues to protect the underlying metal. For these reasons, painted or powder-coated steel is not recommended for rooftop PV systems, as it deviates from established best practice and carries higher long-term performance risks.

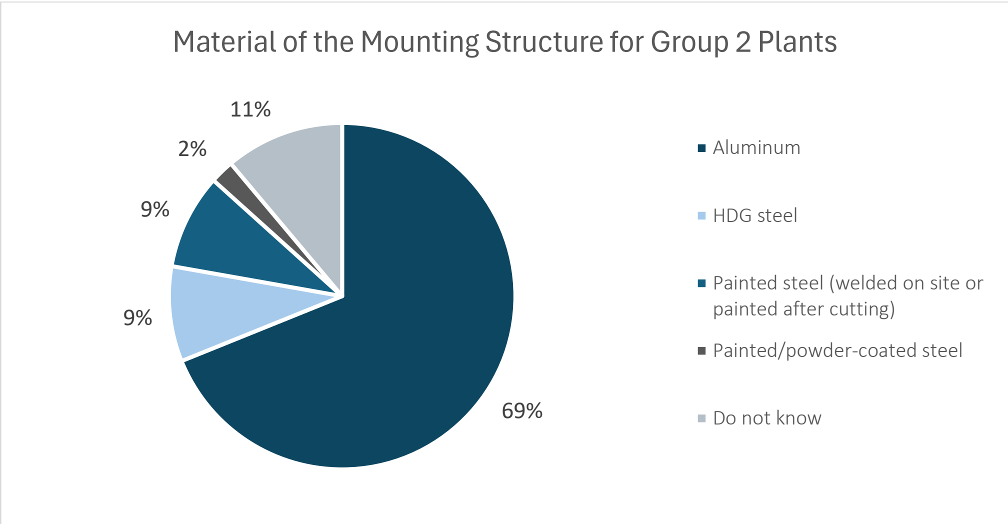


Figure 60: Material of the mounting structure for Group 2 plants

Among the five (5) plants using painted steel as structure material, to be noted that one (1) had already presented rust at cut edges or welded joints.

4.5.4 Failures Leading to Replacement

Across the PV plants in Group 2, only seven reported component failures necessitating their replacement.

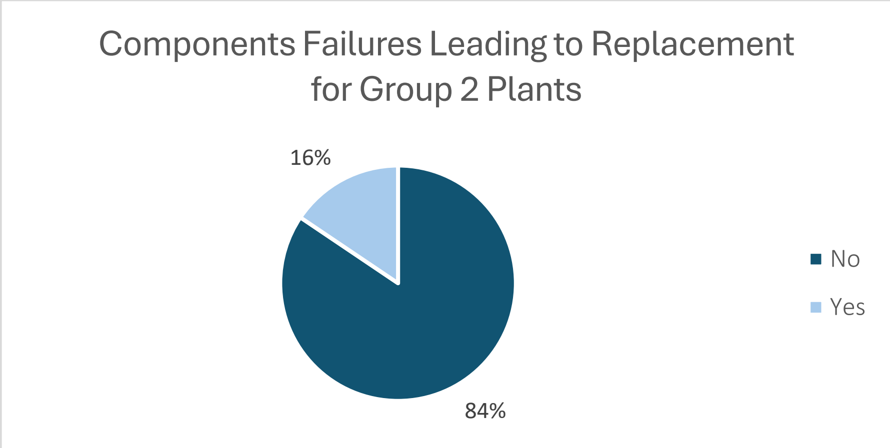


Figure 61: Component failures leading to replacement for Group 2 plants

The failures were distributed as follows: four cases related to inverters, two to electrical connections, and one to a module; however, no further information was disclosed regarding the specific causes or failure mechanisms behind these replacements.

4.6 O&M

4.6.1 General Strategy

Most of the surveyed PV plants (61%), outsource the O&M activities to external companies. However, almost a quarter of the plants (23%) reported that they had never been inspected. The never inspected plants have a Commercial Operation Date (COD) ranging from March 2021 to December 2024, meaning that at least one full operational year had passed prior responding to the survey's questionnaire. This raises serious concerns and highlights the need to strengthen owner-led O&M practices as well as to better inform owners about the necessity and importance of regular inspection.

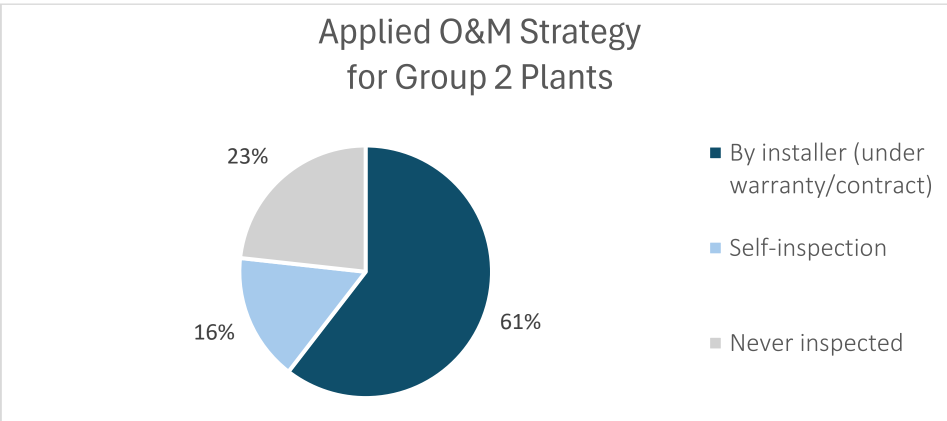


Figure 62: Applied O&M Strategy for Group 2 plants

4.6.2 Cleaning of PV Modules

The responses regarding PV module cleaning practices for the Group 2 PV plants sample are presented in Figure 63.

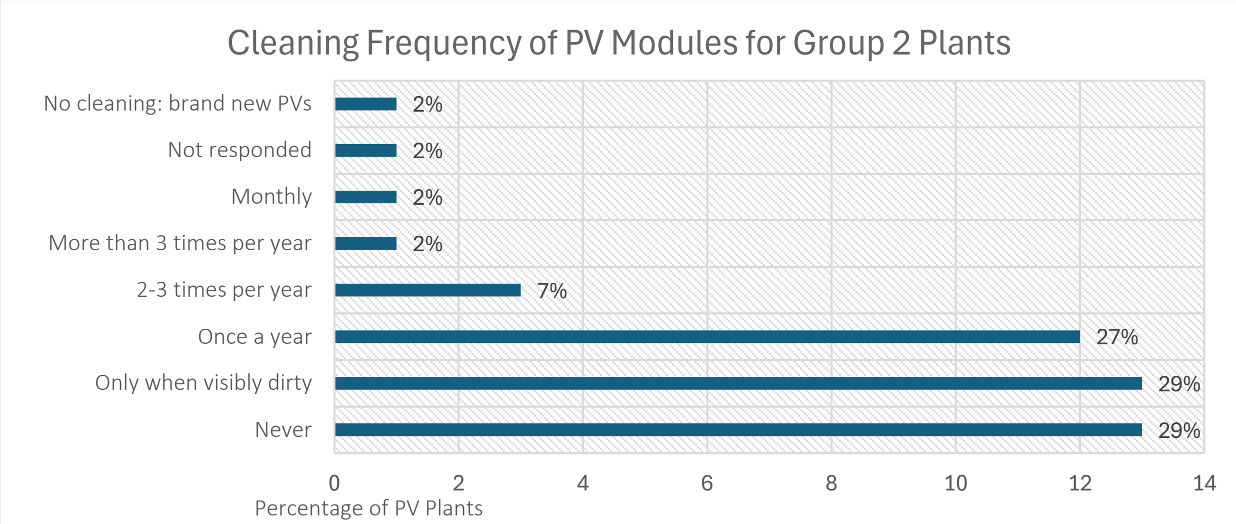


Figure 63: Frequency of cleaning the PV modules for Group 2 plants

A considerable portion of plant owners either never clean their PV modules (29%) or perform cleaning only clean when visibly dirt is observed (29%), which is of course quite subjective. Another 27% clean their modules once per year. More frequent scheduled cleaning is uncommon: only three plants (7%) conduct cleaning 2–3 times per year, one plant (2%) cleans more than three times per year, and one plant (2%) implements monthly cleaning. Additionally, in one case, cleaning had not yet been performed because the plant was still brand new. Overall, the level of cleaning activity is below expectations, which may lead to avoidable energy production losses due to soiling, as well as accelerated equipment degradation. This issue becomes more concerning when considered alongside the finding that 13% of the PV plants are not inspected at all regarding module condition (refer to Section 4.5.1). Furthermore, among the plants that do carry out cleaning, water-based methods dominate, accounting for a combined 75% of all cleaning approaches. Specifically, water alone is used by 39%, while water combined with a soft brush or cloth is applied in 36% of the cases.

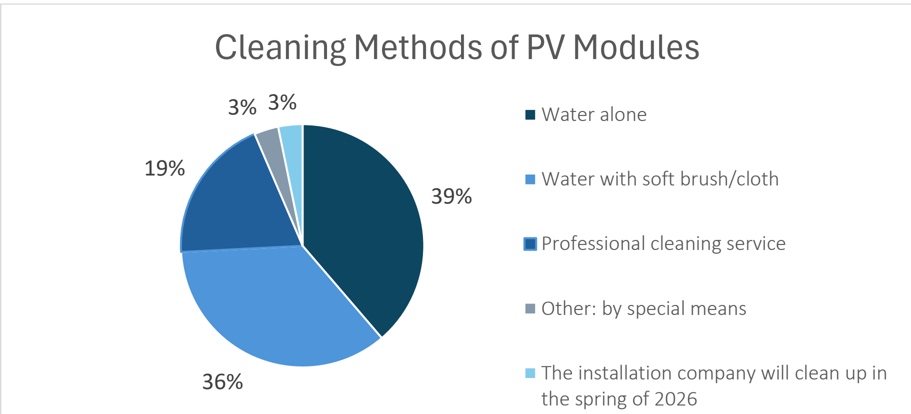


Figure 64: Cleaning methods of PV modules of Group 2 plants

More insights about the suggested cleaning frequency and practices are detailed in Section 3.4.1 for Group 1 plants.

4.6.3 Thermographic Imaging Inspection of PV Modules

Out of seven responses (only a cluster of the PV plants replied to this specific query), about 43% have conducted thermographic inspections with no issues identified, while 29% have not carried them out, and 14% plan to do so. The remaining 14% did not reply, indicating that thermography is still limited rather than standard practice.

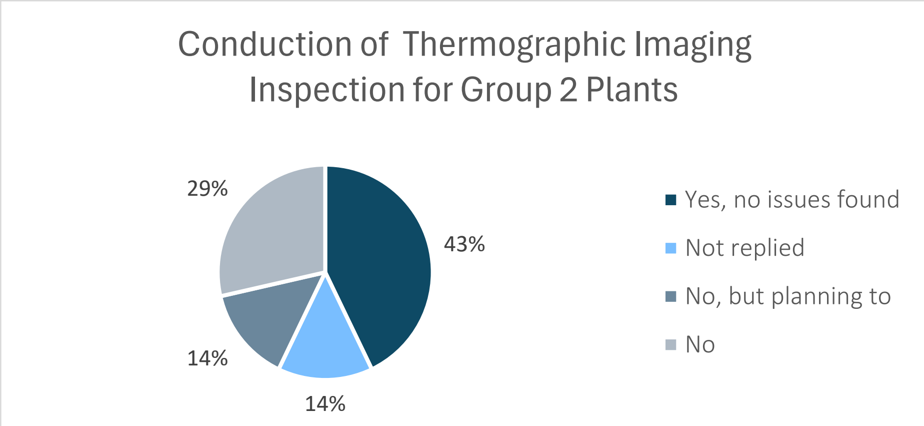


Figure 65: Conduction of thermographic imaging inspection of the PV modules for Group 2 plants

4.7 Grid Interconnection

4.7.1 Grid Quality

Regarding grid operation, more than half of the plants reported stable performance with no significant issues. Around one in four plants noted the occurrence of grid outages, which in some cases affected operational continuity. In addition, five plants reported challenges related to metering equipment quality, with some impact on the accuracy of energy measurements. Further grid-related observations included voltage fluctuations in three plants and curtailment in three other plants.

Overall, grid quality across the Group 2 plants appear to be generally adequate. Moreover, given that the duration of curtailment events and grid outages was not disclosed, their overall magnitude and impact cannot be fully assessed.

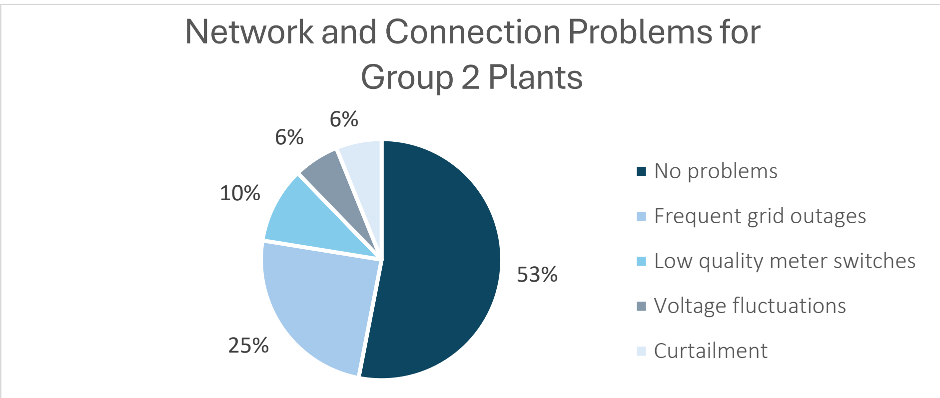


Figure 66: Network and connection problems for group 2 plants

4.7.2 Condition of Grid Infrastructure

When asked about the condition of the existing electrical infrastructure to which the new PV plants were interconnected, the replies were summarized in Table 9.

Reply	Appearances
Everything looks new and properly enclosed	30
Haven't checked / Don't know where to look	11
Old or rusty electrical cabinets, boxes, switches, circuits, transformers	2
Loose or disconnected wires	1

Table 9: Condition of electrical infrastructure to which the PV plants of group 2 were interconnected

A negative concern is that in 11 cases, representing the 25% of the sample the respondents have not checked or did not know where to check in order to determine the condition of the interconnection substation. This highlights the need for improved education and awareness among plant owners.

4.7.3 Injection to the Grid

The data show that net metering clearly dominates, with most systems exporting electricity to the grid (40 out of 45). Direct-consumption-only systems are rare (3 cases), indicating that grid export is the prevailing approach, while the few non-responses do not actually affect the overall conclusion. In general, it is suggested that all plants apply net metering, in order to sell to the grid any excess production and benefit from it financially.

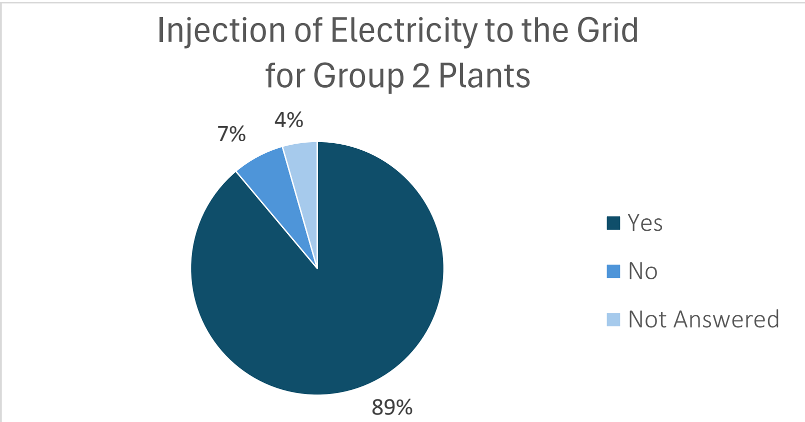


Figure 67: Injection of electricity to the grid for Group 2 plants

4.8 Weather & Environmental Issues

Among the 45 plants investigated, only 15% (9 plants) experienced any weather-related issues.

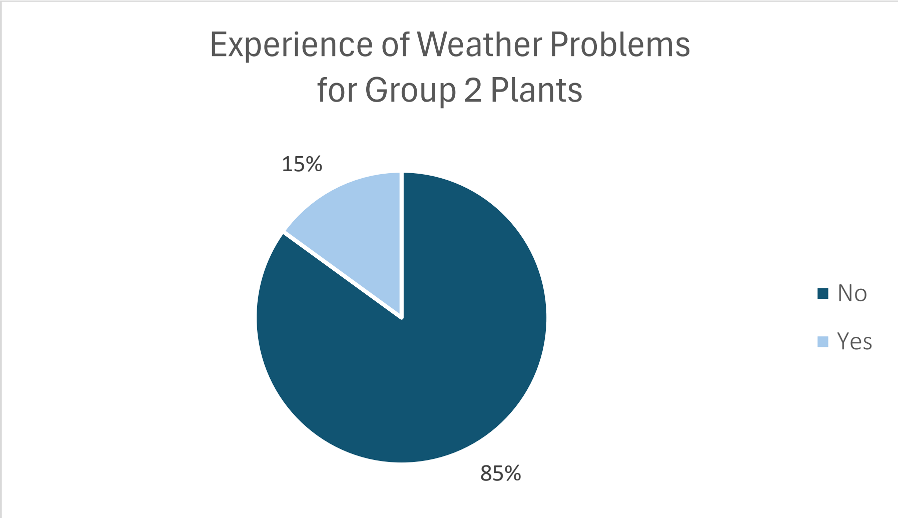


Figure 68: PV plants experienced weather problems for group 2 plants

For the plants that experienced weather-related issues, the types of problems and their frequency are shown in Figure 69 Multiple issues could be reported for the same site. Dust storms were the most common weather-related problem, affecting seven plants and highlighting the need for regular, planned module cleaning. Heavy snowfall was reported twice, covering the modules, reducing output, and potentially adding structural stress if not cleared in time. Extreme heat was also reported in two cases, causing inverter overheating and temporary performance losses.

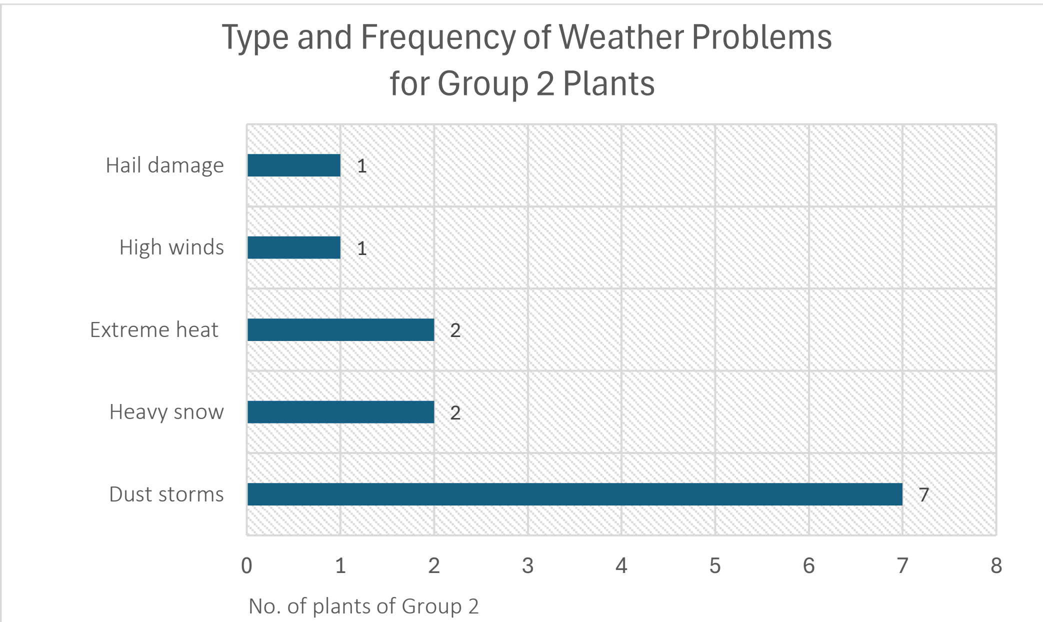


Figure 69: Type and frequency of encountered weather problems for Group 2 plants

Regarding environmental and animal-related issues, most plants reported no problems (35 plants). Among the identified issues, bird-related impacts—such as nesting and droppings—were the most frequent (5 plants). Insects or wasps forming nests and vegetation encroachment were each observed at two plants, while dust accumulation from nearby activities was reported only once. As with weather-related dust, bird droppings require regular cleaning to prevent production losses.

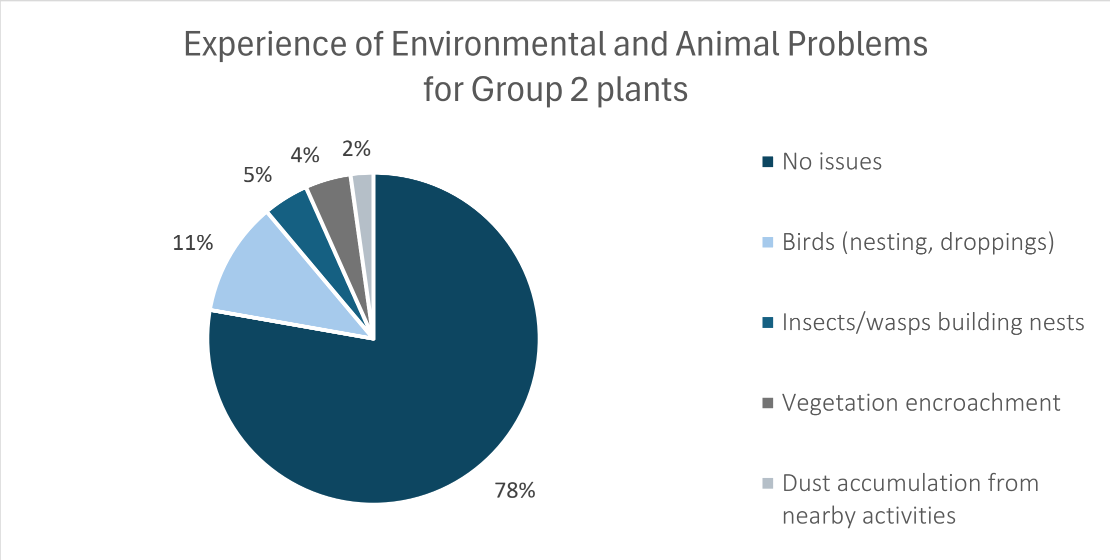


Figure 70: Experience of Environmental and Animal Problems for Group 2 plants

4.9 Safety Problems and Features

The PV plant operators were asked whether they had experienced any of the following safety issues:

- Exposed electrical terminals or connections (e.g., in the basements or utility areas) that you could be accidentally touched
- Burn marks or melted components
- Hot spots on panels or other equipment
- Unusual smells from the inverter or electrical components
- Sparking or buzzing noises
- Rust or water damage near electrical equipment

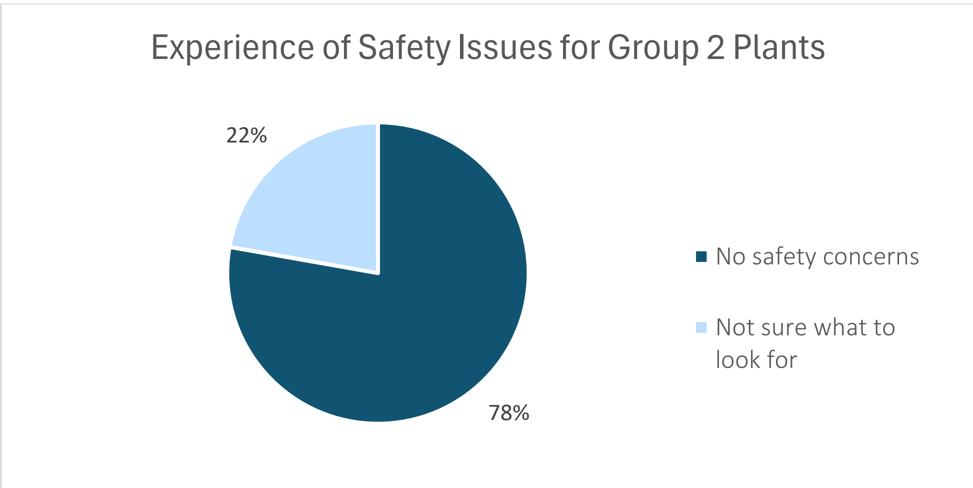


Figure 71: Experience of safety issues for Group 2 plants

Based on the responses, most plants reported no safety-related problems. However, a notable 22% of respondents (10 plants) stated that they do not know what to look for when checking for potential safety issues. This lack of awareness represents a possible risk and highlights the need for better training and clearer maintenance guidelines for plant operators.

Beyond identifying safety problems, the survey also assessed the adoption of key safety systems designed to prevent accidents, protect equipment, and minimize fire and electrical hazards. The reported adoption rates among plants are summarized in Figure 72.

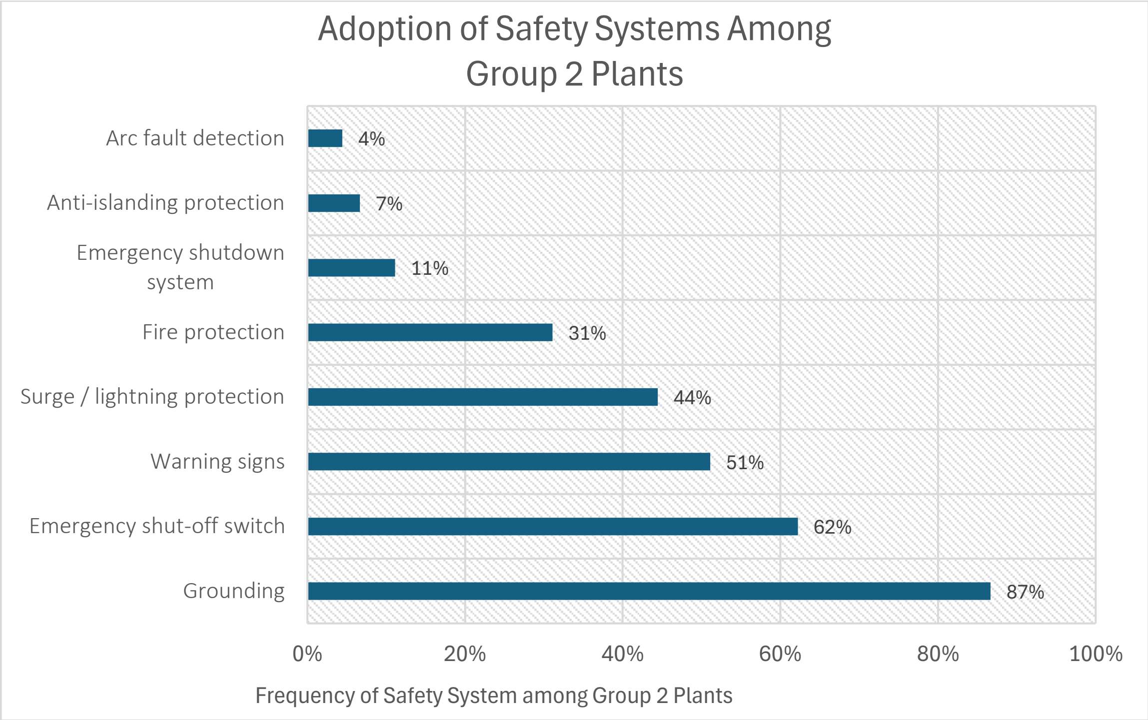


Figure 72: Adoption of safety systems among Group 2 plants

These results highlight significant gaps in the implementation of critical safety features. Several of the systems with the lowest adoption rates—such as arc-fault detection and anti-islanding protection—are essential for preventing fires, protecting utility workers, and ensuring grid stability. Likewise, low adoption of emergency shutdown systems limits operators' ability to respond quickly in the event of equipment failure or fire. Even fire protection and surge/lightning protection, which are standard in well-maintained PV installations, remain below optimal levels.

Grounding and emergency shut-off switches show higher adoption, but the lack of widespread implementation of other protective measures presents clear safety vulnerabilities. Strengthening these systems is crucial not only for preventing accidents but also for improving plant reliability, reducing downtime, and ensuring compliance with modern PV safety standards.

4.10 Investment and Savings

The investment cost in AMD per kW_{DC} of installed capacity for Group 2 plants is presented in Figure 73. It is clearly evident that the plants benefit from economies of scale, resulting in a lower cost per unit of installed capacity as the plant size increases.

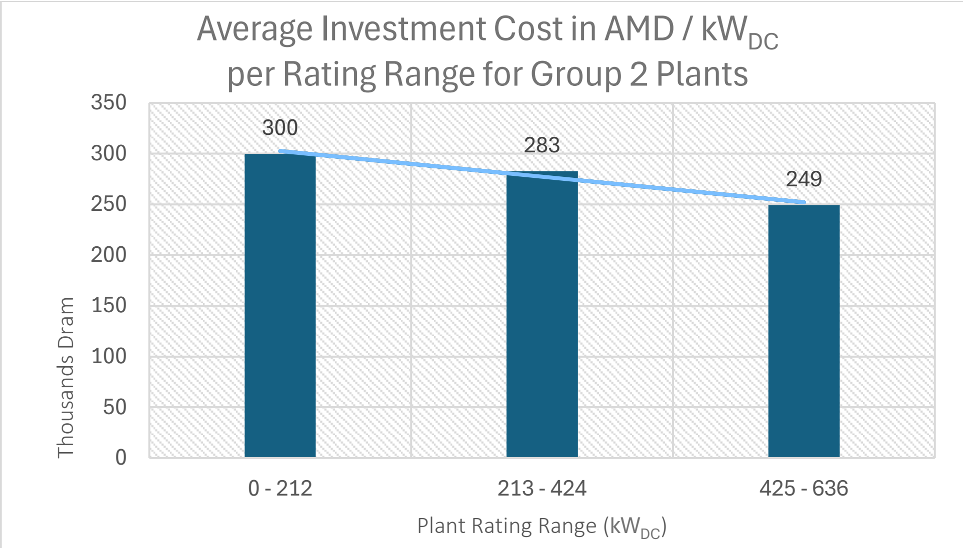


Figure 73: Investment cost in AMD per installed capacity in kW_{DC}

The installation of PV systems has generally led to noticeable reductions in electricity bills. About 58% (26 systems) report significant savings, and 20% (9 systems) see moderate savings. A small share experienced less savings than expected (4%) or just met expectations (16%). Overall, most users benefit at an important extent financially from their PV installation highlighting that the investment is absolutely reasonable.

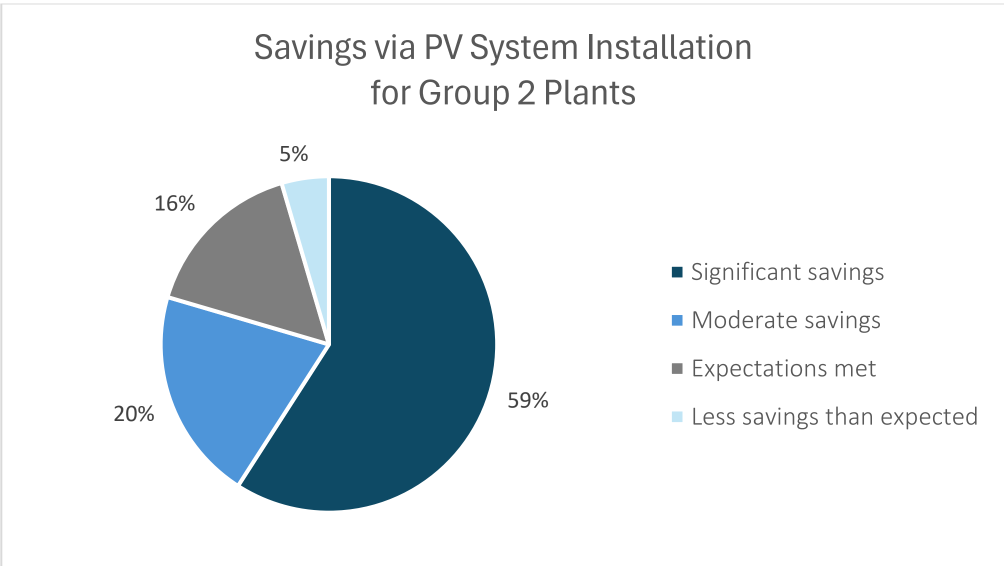


Figure 74: Saving via PV system installation for Group 2 plants

4.11 Overall Satisfaction and Lessons Learned

Overall, 94% of plant owners reported being satisfied or very satisfied with their plants, indicating that they made the right decision to develop such a project. Only one plant owner was neutral and one was very dissatisfied, together representing just 6% of the cases.

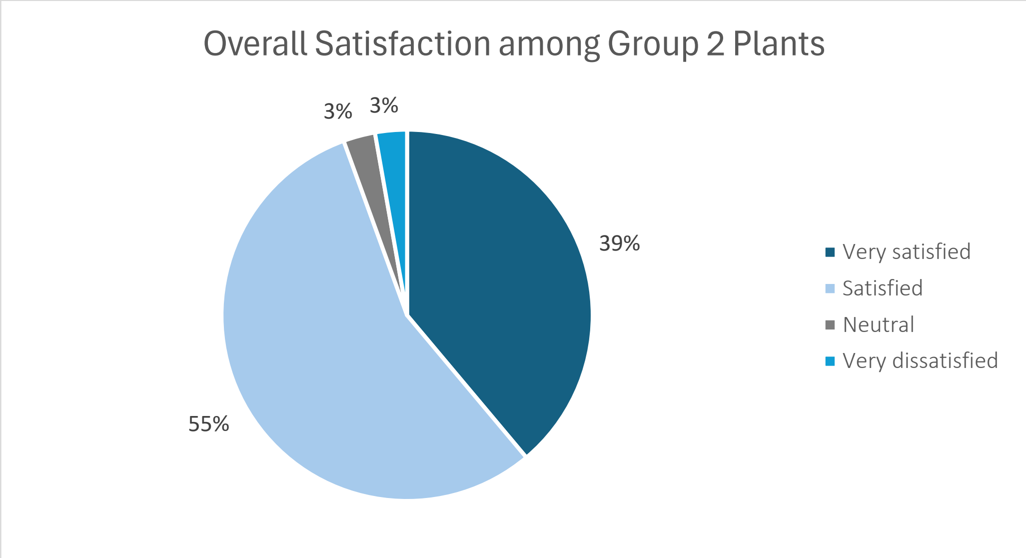


Figure 75: Overall satisfaction among Group 2 PV plants

When asked what they would do differently, 29% of respondents indicated they would not change anything. Nearly 18% would opt for a larger plant, while 7% would focus on improving efficiency. In addition, one respondent would add battery storage, and another would correct the PV tilt, which was identified as inappropriate.

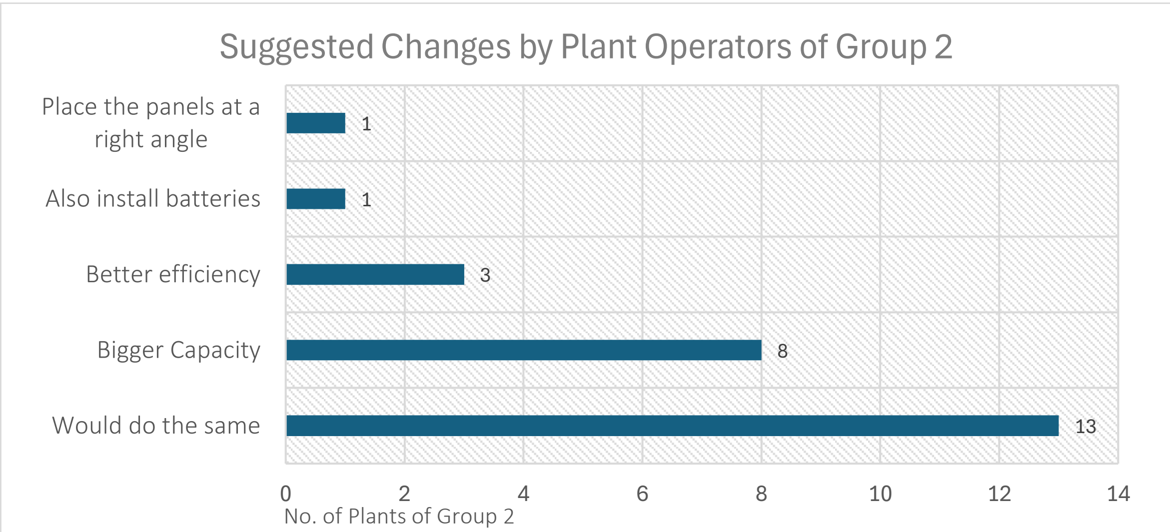


Figure 76: Suggested changes by plant operators of Group 2

The PV plants owners were also asked about the advice they would give to others considering constructing a PV plant. The primary focus for those planning a small PV system is simply to get the system installed, reflecting the participants' general satisfaction with the current operational setup. Secondary considerations include ensuring high-quality components and installing waterproof foundations. Regarding system sizing, recommendations were contradictory: two plants advised selecting capacity based on actual needs, while one plant suggested opting for the maximum possible capacity.

Lastly, plants were asked about potential knowledge gaps they may have Figure 77 shows that only 15 plants (34%) feel adequately informed, indicating that a substantial share of operators still lack sufficient knowledge. The knowledge gaps mostly regard O&M activities, including cleaning and maintenance, performance monitoring as well as safety checks or self-conducted troubleshooting. Finally, support with organizational matters—such as understanding metering bills and navigating the warranty claims process—is also highly valued.

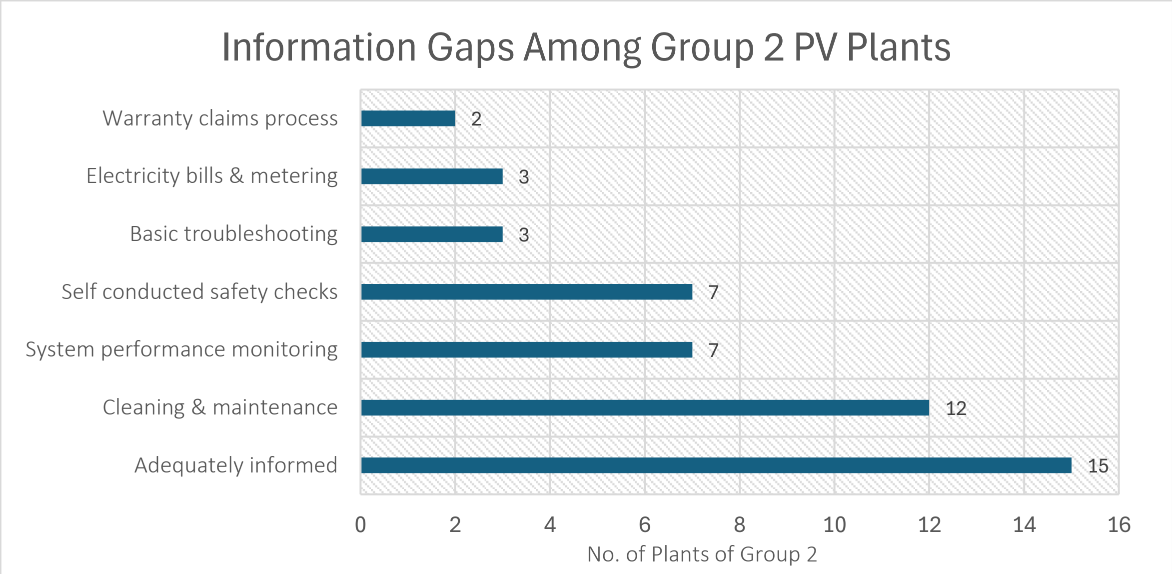


Figure 77: Knowledge gaps identified from Group 2

4.12 Follow-up Engagement

Most respondents were unwilling to participate in a phone call, with 25 answering "No." Only 6 responded "Yes," while 13 indicated potential interest. This reluctance is concerning, as data exchange plays an important role in improving future PV projects.

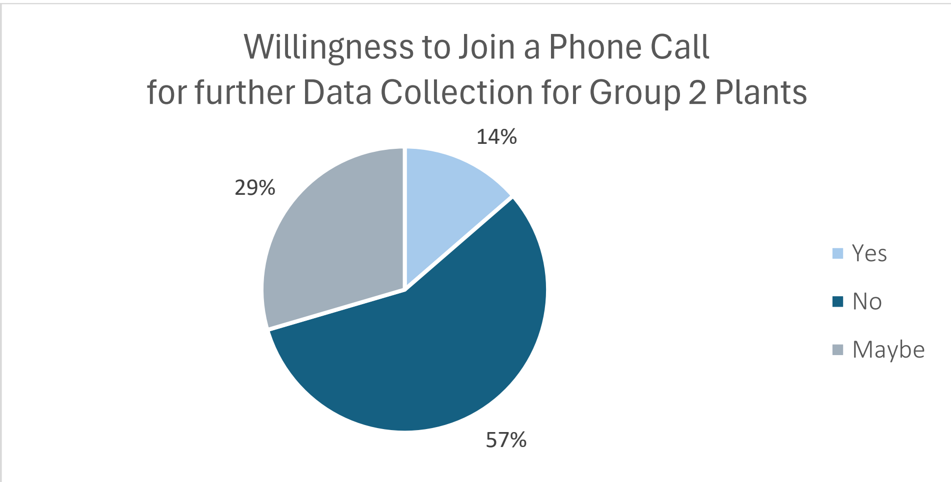


Figure 78: Willingness to participate in a phone call for further data collection for Group 2 Plants

On the other hand, most respondents were open to a site visit to document the system, with 27 answering "Yes." A small number declined (3), while a significant share (14) indicated potential willingness by selecting "Maybe." In general, a site visit by a PV expert can lead to more accurate findings and further support the questionnaire survey.

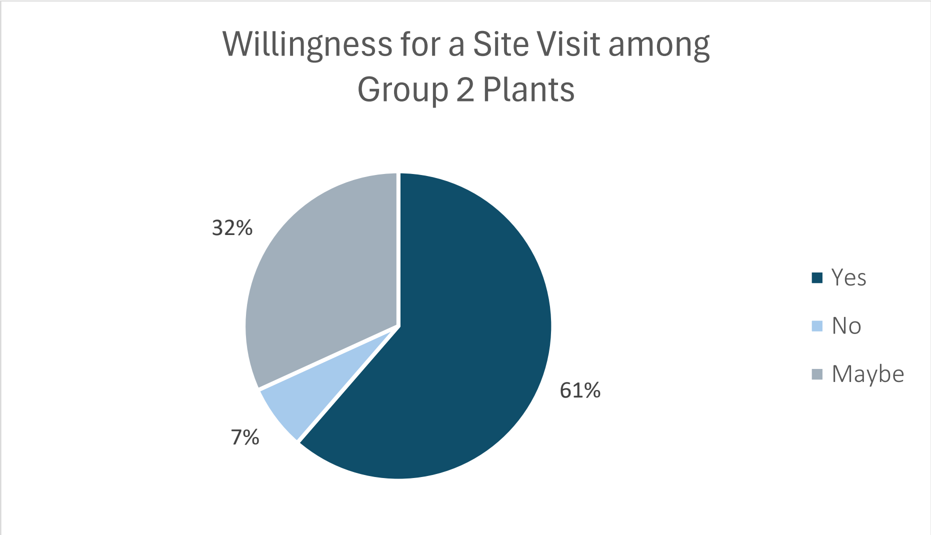


Figure 79: Willingness for a site visit among Group 2 plants

5 Main Findings

Having analysed the data received from the PV plants, this section aims to present the main findings by group and topic, along with relevant commentary. Moreover, the findings are classified using a three-type colour coding system.

- Green → meets expectations
- Yellow → partially meets expectations / refinement recommended
- Orange → does not meet expectations /action required

5.1 Group 1 PV Plants

Regarding Group 1 PV plants, the main findings are summarized in Table 10 below.

Code	No	Topic	Observation	Comment
(Green)	1	Selection of OEMs	Tier 1 OEMs selected in all plants of Group 1.	This is a positive indicator, as experienced OEMs typically offer proven technologies, higher reliability, and well-established quality standards. In addition, they ensure better availability of spare parts, technical support, and long-term service agreements, reducing operational risks and downtime.
(Yellow)	2	Weather station	Although weather stations are installed at the majority of the plants (84%), an important portion of them (44%) are not using the weather station for performance monitoring. In terms of measured parameters these were as follows: ▪ Frequently measured: GHI, ambient temperature, wind speed/direction, and relative humidity (27/32 plants).	Potential added value is lost: ▪ Higher uncertainty due to reliance on modelled/satellite data. ▪ Risk of masking operational issues. ▪ Reduced ability to detect underperformance linked to environmental factors (e.g., soiling, shading, abnormal temperature effects). ▪ Weakened foundation for predictive maintenance strategies. ▪ It is important to ensure that operators understand the added value of performance monitoring based on actual weather station data. Furthermore, expanding the weather

Code	No	Topic	Observation	Comment
			Less frequently measured: GII (5 plants), module temperature (4 plants), and PM10, PM2.5, and rain/snow (3 plants each).	station's measurement capabilities—for example, by including module temperature—can significantly enhance overall monitoring accuracy and insights.
	3	Deviation from Expected Performance	Only 9.4% of the surveyed plants experienced deviation: ▪ -25 to 30% (grid related downtime and transformer failures) ▪ -17% (overestimated yield) ▪ +5% (positive)	The results indicate that the EYA was properly assessed during plant design. Only one case showed a significant deviation of 17% due to an overestimated yield. The other problematic case was caused by grid-related downtime and the failure of critical components, specifically transformers. Overall, a robust EYA is critical to ensure that projected plant performance is realistic and bankable. It directly influences investment decisions, financing terms, and overall project viability by reducing uncertainty in expected energy production. Accurate and conservative EYAs also support optimized plant design and help align long-term operational performance with initial forecasts, minimizing the risk of underperformance over the project lifetime.
	4	Failures of PV modules	▪ 37% of surveyed PV plants reported module failures ▪ Broken glass is the leading issue (31.25%) ▪ Connectors/cables and junction boxes each account for 25% ▪ Microcracking: 12.5% ▪ Lightning damage: 6.25% (least common)	Overall, the reported failures are consistent with the types of issues typically observed in utility-scale PV systems of comparable age. For plants operating between 4 and 8 years, early field degradation phenomena are expected to begin appearing, particularly in components such as connectors and junction boxes, which are among the most common sources of reliability problems in the industry. Likewise, occasional glass breakage or weather-related mechanical damage is not unusual at this stage of operation. However, since a detailed root cause analysis was not available in most cases, the severity of the failures cannot be precisely assessed.

Code	No	Topic	Observation	Comment
	5	Failures of Inverters	▪ >53% of plants experienced significant inverter failures, making them a major source of operational disruptions ▪ Circuit boards and power electronics dominate failure causes, while cooling, software, communication, and protection issues are only sporadic. ▪ Average downtime: 12.2 days per inverter failure, significantly impacting production and revenues. ▪ Spare parts readiness: 14/15 plants resolved issues using own inventory ▪ OEM support: Warranties honoured in all cases; response times ranged 2–60 days (avg. 27 days)	▪ The findings align with industry-wide observations that inverters remain the component most prone to early-life failures and operational disruptions. Specifically, for plants operating between 4 and 8 years, a measurable number of inverter failures is not unexpected, as this period often captures the transition from early-life to mid-life reliability behaviour. ▪ Resolving failures using own spare parts indicate strong maintenance preparedness. ▪ Positive finding that warranties were honoured in all cases. ▪ The average downtime due to inverter problems is significant and highlights the criticality of the component. More systematic preventive maintenance would help reduce downtime. This includes routine checks of cooling systems, ventilation paths, and filter conditions, as well as verification of cable terminations and grounding. Establishing a structured process for firmware updates (e.g. tested on a limited number of units before wider rollout) can also reduce the risk of software-related interruptions. Maintaining adequate stocks of critical spare parts such as control boards or fans enables faster corrective interventions. Enhanced monitoring of inverter operational parameters can also support earlier detection of abnormal behaviour.
	6	Failures of Mounting Structures & Trackers	▪ No issues related to mounting structures were reported among the plants of Group 1. ▪ Among the seven plants equipped with tracker systems, only one reported a failure, specifically involving the control system.	Structural components have generally performed reliably within the 4–8 year operational window. This result aligns with expectations, as mounting structures, when properly designed and installed, typically exhibit low failure rates during early and mid-life operation, with most issues emerging only under extreme weather events or long term corrosion processes.

Code	No	Topic	Observation	Comment
	7	Failures of transformers, switchgear, protection devices, and SCADA systems	▪ Transformer issues were encountered in four plants, representing 12% of the PV plant sample. ▪ In terms of switchgear and protection equipment, issues were reported in 5 plants (16%). ▪ Regarding the SCADA system, a total of 4 malfunctions were reported.	▪ Failures reported in transformers, switchgear, protection devices, and SCADA systems were relatively limited in number but point toward a recurring pattern linked to grid-quality challenges, particularly voltage fluctuations and harmonics. Several transformer issues ranging from overcurrent damage to the activation of protection systems, appear to be influenced by unstable grid conditions rather than intrinsic equipment design flaws. Likewise, SCADA malfunctions in a plant were caused due to excessive voltage levels. ▪ Therefore, in addition to proper inspection and maintenance, enhancing coordination with the grid operator, improving monitoring of power-quality events, and reinforcing preventive maintenance of protection systems can help reduce the likelihood and impact of similar issues in the future.
	8	Cleaning of PV Modules	More than half (52%) of the PV plants do not clean the modules, 9 plants (28%) clean based on performance monitoring, 6 plants (19%) clean bi-annually, and 1 plant (3%) follows other cleaning practices.	Overall, the cleaning frequency is insufficient. Ideally, it should range from 2 to 4 times per year, while areas with higher dust levels may require cleaning 4 to 6 times annually. In rainy regions, natural cleaning reduces the needed frequency for manual cleaning.
	9	Vegetation Management	All plants where vegetation management was applicable were actively implementing it, with an average frequency of 2.2 times annually	The average frequency is generally in line with good practices, while remaining location-specific. This is an important measure to prevent shading, reduce the risk of hotspot development, and enhance safety by minimizing dry vegetation, particularly during the summer months.
	10	Annual O&M Cost	All plants (with a single exclusion) claimed investment in line with the expectation.	This indicates that OPEX was properly estimated during plant development. Furthermore, as expected, the plants benefited

Code	No	Topic	Observation	Comment
				from economies of scale, presenting lower cost per MVA_{AC} for increasing plant capacity..
	11	O&M Difficulties	Almost half of the plants (47%) declared as not having access to qualified technicians. Further common experienced difficulties among the plants (22%) were also: ▪ Spares availability. ▪ Site access issues. ▪ Equipment reliability.	It is very crucial to increase the available workforce of technicians in Armenia and provide them with proper training. Moreover, to address the other identified challenges, ensuring proper O&M planning, maintaining adequate and easily accessible spare parts and engaging reputable OEMs for equipment supply, is essential.
	12	Storage of Spare Parts	▪ Offsite storage only: 16 plants store spare parts offsite. ▪ Hybrid storage (onsite & offsite): 5 plants manage spare parts both onsite and offsite. ▪ Onsite storage only: 5 plants keep all spare parts exclusively onsite. ▪ No storage: 6 plants do not store spare parts, as O&M is fully outsourced to external service providers.	▪ Storing spare parts offsite is generally acceptable if the location is nearby; however, in eight PV plants where parts are stored more than 50 km away, delays in corrective maintenance may occur. In general, larger or less frequently replaced components can be stored offsite, provided the distance remains reasonable (typically <25 km) and clear response-time commitments are in place. ▪ For plants that fully outsource their O&M, the absence of on-site stock is not uncommon, but it must be compensated by robust LTSAs and verifiable inventory availability.
	13	GAF-RE Funding	All plants expressed satisfaction with the GAF-RE funding. Improvement suggestions included: ▪ faster decision-making (5 plants) ▪ lower loan interest rates (8 plants)	The overall satisfaction is also reflected in the willingness to seek future funding from GAF, with 80% of plants willing to seek future GAF funding for renewable energy and BESS projects, 10% unwilling, and 10% not yet read.

Code	No	Topic	Observation	Comment
	14	Grid Availability	▪ 26 plants (81%) reported downtime, while only 6 plants (19%) remained unaffected. ▪ However, for the plants experiencing downtime, the annual duration ranges between 8 and 32 hours for 50% of the plants, with a median of 26 hours and a maximum of 55 hours.	Even in the worst-case scenario, with an unavailability of 55 hours, the annual availability remains at 99.37%, which is consistent with European standards. Overall, while the frequency of grid downtime may initially appear elevated, the resulting grid availability is sufficiently high and aligned with European standards.
	15	Grid Curtailment	▪ Grid curtailment was reported in one out of four plants (8 cases in total) participating in the survey. ▪ Where it occurred, the impact on annual production was limited, with an average curtailed energy of 0.54% and a maximum of 1.23%, indicating a minor overall effect on energy yield. ▪ Curtailment was primarily driven by general grid conditions (planned maintenance, unplanned outages, and grid congestion/weak local grid). Only in three cases did it occur due to congestion during peak renewable generation hours.	Curtailment incidents were limited and had a minor impact, mainly driven by grid conditions rather than excessive renewable penetration, indicating potential for further renewable integration. Integrating Battery Energy Storage Systems (BESS) can help balance supply and demand, reduce curtailment, and improve grid stability, supporting smoother renewable integration and enhancing overall system resilience.
	16	Regulatory Challenges	Only one plant faced significant regulatory challenges (prolonged process) regarding land permit, plant category classification and grid access. Hence, limited proposed improvements: ▪ Clearer shutdown regulations (6 plants) ▪ Simpler electronic data submission system (6 plants) ▪ Centralized permitting support system (2 plants)	Quite positive experience in total for a typical project bottleneck. Nevertheless, relevant authorities should review and assess the PV plants' suggestions to further simplify the process.

Code	No	Topic	Observation	Comment
			▪ Single-window system for all document submissions (1 plant)	
	17	Environmental Issues	Only one reported environmental issues, specifically soil erosion, which required the addition of large gravel to mitigate and slow down the erosion process.	Non-occurrence of environmental problems indicates proper and thorough environmental assessment prior project construction.
	18	Health and Safety	▪ No incidents reported. ▪ All plants have HSE plan with is followed without challenges.	No issues were observed for a topic of utmost importance. Adherence to HSE requirements without any incidents also indicates that plant operators and the workforce are adequately informed and trained.
	19	Community Relations	All respondents reported either a very positive (19 plants) or positive (13 plants) relationship with local communities, although social engagement activities were rare among the respondents (3 cases).	Solar energy seems to enjoy a strong local acceptance in Armenia, paving the way for further project developments. Nevertheless, it remains essential to keep local communities well-informed and actively engaged throughout the process.
	20	Formal Grievance Plan	Only 37% of the surveyed plants responded that they have a formal grievance management.	This practice shall be expanded to all plants to address and resolve community complaints promptly and fairly.
	21	Follow-up Engagement	In total, 97% of the respondents were willing to share documentation in order to support the survey, including mainly monthly energy production data and in some cases maintenance logs and O&M reports. In terms of conducting a brief site visit to verify certain aspects of the plant, the vast majority of plant owners were positive, 87%.	This openness reflects a collaborative, improvement-focused mindset among PV plant owners, facilitating data sharing and the exchange of lessons learned.

Table 10: Main findings and their classification for Group 1 PV plants

5.2 Group 2 PV Plants

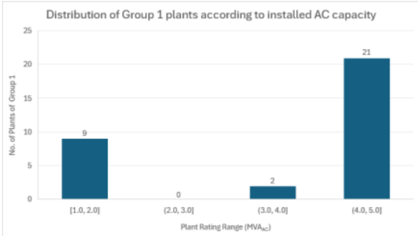
Regarding Group 2 PV plants, the main findings are summarized in Table 11 below.

No	Topic	Observation	Comment
1	O&M Strategy	Most of the surveyed PV plants (61%), outsource the O&M activities to external companies. However, almost a quarter of the plants (23%) reported that they had never been inspected. The never inspected plants have a COD ranging from March 2021 to December 2024, meaning that at least one full operational year had passed prior responding to the surveys' questionnaire.	No inspection for years raises serious concerns and highlights the need to strengthen the owner-led O&M practices, as well as to better inform owners about the importance and necessity of regular inspection.
2	Module Cleaning	A considerable portion of plant owners either never clean their PV modules (29%) or perform cleaning only clean when visibly dirt is observed (29%), which is of course quite subjective. Another 27% clean their modules once per year. More frequent scheduled cleaning is uncommon	Overall, the cleaning frequency is insufficient as commented also for Group 2 plants. Ideally, it should range from 2 to 4 times per year, while areas with higher dust levels—common in Armenia—may require cleaning 4 to 6 times annually. In rainy regions, natural cleaning reduces the needed frequency for manual cleaning.
3	Performance Monitoring Method	Monitoring was dominated by mobile applications, used by 96% of systems. Other methods included the inverter display (13 plants) and the electricity meter (10 plants), while only three plants used a web platform and one relied on an external third-party calculation.	It is encouraging that there is a clear tendency toward user-friendly monitoring, either through a mobile app or the inverter display, as these provide the quickest way to track production on a daily basis. For systems of such small scale, these methods are also the simplest and most intuitive for domestic or commercial users.

No	Topic	Observation	Comment
4	Performance Monitoring Frequency	All PV plants monitor their energy production, with the following responded frequency: ▪ 64% monitored energy production on a weekly basis. ▪ 25% checked production monthly. ▪ 11% monitored energy production daily.	Daily monitoring of energy production would allow plant owners to identify potential issues at an early stage and take prompt corrective actions, thereby minimizing energy losses and improving overall system performance.
5	System Installation	The survey indicated high satisfaction with PV installation companies, with 93% of respondents reporting they were very satisfied or satisfied. The installation process was generally smooth, as only 4% reported issues. In addition, 25 different installation companies were represented in the survey	The installation experience among PV plants was generally smooth and satisfactory. Moreover, the presence of numerous installation companies in the market can potentially facilitate competitive pricing.
6	Roof Inspection prior to Installation	In terms of roof inspection prior to PV system installation, about one quarter (22%) of the roof-mounted PV plants relied solely on a visual check by the installer.	This practice poses structural risk since it cannot fully identify all problems. The recommended engineering practice is to conduct a roof inspection that includes structural calculations—such as estimating dead loads, wind loads, and snow loads—reviewing the building's structural drawings, and comparing the calculated loads with the requirements of the applicable building codes.
7	Material of Mounting Structure	Aluminium, being a lightweight and corrosion-resistant solution, is used in 69% of the cases (39 plants). Galvanized steel follows with 9% (4 plants), while in 11% of the cases (5 plants) the owners were not aware of the material. Another	For such applications, industry best practice is to use aluminium profiles or hot dip galvanized (HDG) steel components, as both offer proven long term durability under outdoor exposure. Aluminium is widely preferred for rooftops because it is lightweight, naturally corrosion-resistant, and easy to handle on

No	Topic	Observation	Comment
		11% (5 plants), which were all rooftop installations, used either painted or powder-coated steel.	buildings with limited load capacity. HDG steel is also acceptable, but it is heavier and therefore less common on roofs. In contrast, painted or powder coated steel provides only surface level protection that can be easily damaged during transport or installation. Once the coating is compromised, corrosion begins quickly, which shortens the service life of the mounting system and increases maintenance requirements. Hence, it is not recommended for roof-mounted systems.
8	Grid Quality	The frequency and type of grid related issues is as presented below: ▪ 53% reported no issues. ▪ 25% experienced grid outages. ▪ 10% complained about low quality meters ▪ 6% experience curtailment ▪ 6% experienced voltage fluctuations.	Overall, grid quality across the Group 2 plants appear to be generally adequate, without a major negative and persistent finding. Moreover, given that the duration of curtailment events and grid outages was not disclosed, their overall magnitude and impact cannot be fully assessed.
9	Safety Issues	Plants were asked whether they had any safety related issues including the following: ▪ Exposed electrical terminals or connections (e.g., in the basements or utility areas) that you could be accidentally touched ▪ Burn marks or melted components ▪ Hot spots on panels or other equipment ▪ Unusual smells from the inverter or electrical components	This lack of awareness represents a possible risk and highlights the need for better training and clearer maintenance guidelines for plant operators

No	Topic	Observation	Comment
		▪ Sparking or buzzing noises ▪ Rust or water damage near electrical equipment Most plants reported no safety-related problems. However, a notable 22% of respondents (10 plants) stated that they do not know what to look for when checking for potential safety issues.	
10	Adoption of Safety Systems	The adoption of safety systems among Group 2 PV plants is as follows: ▪ Grounding: 87% ▪ Emergency shut-off switch: 62% ▪ Warning signs: 51% ▪ Surge / lightning protection: 44% ▪ Fire protection: 31% ▪ Emergency shutdown system: 11% ▪ Anti-islanding protection: 7% ▪ Arc fault detection: 4%	These results highlight significant gaps in the implementation of critical safety features. Systems with the lowest adoption—such as arc-fault detection and anti-islanding protection—are essential for preventing fires, protecting utility workers, and ensuring grid stability. Similarly, the limited use of emergency shutdown systems reduces operators' ability to respond quickly in case of equipment failure or fire. Fire protection and surge/lightning protection, although standard in well-maintained PV installations, also remain below optimal levels. While grounding and emergency shut-off switches show relatively higher adoption, the limited implementation of other protective measures creates clear safety vulnerabilities. Strengthening these systems is essential for preventing accidents, improving plant reliability, reducing downtime, and ensuring compliance with modern PV safety standards.
11	Initial Investment	The average initial investment in AMD per kW_{DC} for the three size tiers of Group 2 plants is as follows:	It is clearly evident that the plants benefit from economies of scale, resulting in a lower cost per unit of installed capacity as the plant size increases. This is an expected outcome, in line with industry experience.

No	Topic	Observation	Comment
			
12	Achieved Savings	About 58% (26 systems) report significant savings, and 20% (9 systems) see moderate savings. A small share experienced less savings than expected (4%) or just met expectations (16%).	Overall, most users benefit at an important extent financially from their PV installation highlighting that the investment is absolutely reasonable. This underscores the economic viability of PV projects and reinforces their attractiveness as a sustainable energy investment.
13	Knowledge Gaps	Among the PV plants of Group 2 only 15 plants (34%) feel adequately informed, indicating that a substantial share of operators still lack sufficient knowledge. The knowledge gaps mostly regard O&M activities, including cleaning and maintenance, performance monitoring as well as safety checks or self-conducted troubleshooting. Finally, support with organizational matters—such as understanding metering bills and navigating the warranty claims process—is also highly valued.	To bridge the knowledge gaps among operators, targeted training programs should be implemented. These could include hands-on workshops for O&M activities, performance monitoring, and safety procedures, as well as guidance on administrative tasks such as interpreting metering bills and managing warranty claims. Regular refresher sessions and access to digital resources would further reinforce skills and ensure sustained competence across all operators.
14	Net metering	Net metering clearly dominates, with most systems exporting electricity to the grid (40 out of 45). Direct-consumption-only systems are rare (3 cases).	In general, it is positive that plants apply net metering, allowing them to sell any excess production to the grid and benefit financially from it.

No	Topic	Observation	Comment
15	Overall Satisfaction	94% of PV plant owners of Group 2 reported being satisfied or very satisfied with their plants. Only one plant owner was neutral and one was very dissatisfied, together representing just 6% of the total cases.	This general satisfaction is a positive outcome, indicating that PV plant owners made the right decision in developing such projects and leaving the door open for the future expansion of the sector.
16	Follow-up Engagement	Most survey respondents were unwilling to participate in a phone call, with 25 answering "No." Only 6 responded "Yes," while 13 indicated potential interest. On the other hand, most respondents were open to a site visit to document the system, with 27 answering "Yes." A small number declined (3), while a significant share (14) indicated potential willingness by selecting "Maybe."	Overall, the owners of the Group 2 PV plants showed some reluctance regarding data exchange, even though it plays an important role in improving future PV projects. Nevertheless, they appear pretty open in allowing a site visit to their premises.

Table 11: Main findings and their classification for Group 2 PV plants