

Task 13 Reliability and Performance of Photovoltaic Systems

PVPS

PV Project Decisions: Quality, Performance, and Economic Value

2026



What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programmes are made up of 6,000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCPs within the IEA and was established in 1993. The mission of the programme is to “enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems.” To achieve this, the Programme’s participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct ‘Tasks,’ that may be research projects or activity areas.

The 28 IEA PVPS participating countries are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, India, Israel, Italy, Japan, Korea, Lithuania, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Türkiye, the United Kingdom and the United States of America. The European Commission, Solar Power Europe and the Solar Energy Research Institute of Singapore are also members.

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What is IEA PVPS Task 13?

Within the framework of IEA PVPS, Task 13 aims to provide support to market actors working to improve the operation, the reliability and the quality of PV components and systems. Operational data from PV systems in different climate zones compiled within the project will help provide the basis for estimates of the current situation regarding PV reliability and performance.

The general setting of Task 13 provides a common platform to summarize and report on technical aspects affecting the quality, performance, reliability, and lifetime of PV systems in a wide variety of environments and applications. By working together across national boundaries, we can all take advantage of research and experience from each member country and combine and integrate this knowledge into valuable summaries of best practices and methods for ensuring PV systems perform at their optimum and continue to provide competitive return on investment.

Task 13 has so far managed to create the right framework for the calculations of various parameters that can give an indication of the quality of PV components and systems. The framework is now there and can be used by the industry who has expressed appreciation towards the results included in the high-quality reports.

The IEA PVPS countries participating in Task 13 are Australia, Austria, Belgium, Canada, Chile, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Morocco, the Netherlands, Norway, Spain, Sweden, Switzerland, Thailand, and the United States of America.

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COVER PICTURE

Drone shot of PV Power Plant in Castalia, NC, USA. Source: [Drone Shot of a Solar Panels - Free Stock Photo](#) by Mark Stebnicki.



INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Photovoltaic Project Decisions: Quality, Performance, and Economic Value

IEA PVPS Task 13 Reliability and Performance of Photovoltaic Systems

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AUTHORS

Main Authors

David Moser, EURAC Research, Becquerel Institute Italia, Italy
Ulrike Jahn, Fraunhofer CSP, Halle, Germany
Bert Herteleer, KU Leuven, Ghent, Belgium
Leonardo Micheli, Sapienza University of Rome, Rome, Italy
Julián Ascencio Vásquez, Univers, Redwood City, USA
Jan Vedde, European Energy, Denmark
Magnus Herz, TÜV Rheinland, Cologne, Germany
Thore Müller, PVRADAR Labs, München, Germany
Pietro Elia Campana, Mälardalen University, Västerås, Sweden
Elias Urrejola Davanzo, SOLAR FOTOVOLTAICA, Chile
Sascha Lindig, Univers SAS, Courbevoie, France
Ioannis Tsanakas, CEA INES, France
Roger H. French, CWRU, Cleveland, OH, USA
David Brearley, VDE Americas, USA
John Sedgwick, VDE Americas, USA

Contributing Authors

Atse Louwen, Eurac Research, Italy
Jonathan Leloux, Lucisun, Belgium
Laurie Burnham, Sandia National Laboratories, USA
Hamza Maaroufi, TÜV Rheinland, Cologne, Germany

Editors

Ulrike Jahn, Fraunhofer CSP, Halle, Germany
David Moser, Becquerel Institute Italia, Italy



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LIST OF ABBREVIATIONS

AAL	Average annual loss
AC	Alternating current
ACOE	Actual cost of electricity
AEMO	Australian Energy Market Operator
AM	Asset manager
AO	Asset owner
ARENA	Australian Renewable Energy Agency
AV	Agrivoltaic
BC	Business case
CAPEX	Capital expenditure
CfD	Contract-for-difference
CGMPV	Conventional ground-mounted photovoltaic
CO ₂	Carbon dioxide
CP	Captured price
CR	Crop ratio
DC	Direct current
EE	Energy export
EGP	Energy generator potential
EL	Electroluminescence
EoL	End-of-life
EPC	Engineering, procurement and construction
ER	Energy ratio
EUR	Euro
EYA	Energy yield assessment
FCR	Frequency containment reserve
FID	Final investment decision
FM	Financial model
FPV	Floating PV
FT	Fixed tilt
GCR	Ground coverage ratio
GW	Giga watt
ha	hectare
HSAT	Horizontal single axis trackers
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IR	Infrared
IRR	Internal rate of return
IT	Information technology



KPI	Key performance indicator
kWh	Kilo watt hour
kWp	Kilo watt peak
LED	Light-emitting diode
LER	Land equivalent ratio
LID	Light induced degradation
LSS	Large-scale solar
MDS	Materials data science
MLF	Marginal load factor
MPPT	Maximum power point tracking
MTBF	Mean time between failure
MU	Measurement uncertainty
NEM	National Electricity Market
NOAA	National Oceanic and Atmospheric Administration
NPV	Net present value
η_N	Normalised efficiency
O&M	Operation & maintenance
OPEX	Operational expenditure
p.a.	Per annum
PDR	Performance degradation rate
PLR	Performance loss rate
PML	Probable maximum loss
POA	Plane of array
PPA	Power purchase agreement
PR	Performance ratio
PtX	Power to X
Rd	Module degradation rate
RE	Renewable energies
ROI	Return of investment
RRN	Regional reference node
SCADA	Supervisory Control and Data Acquisition
SOH	State-of-health
SP	Specific production
STC	Standard test conditions
TA	Technical advisor
TMD	Typical meteorological data
USD	United States dollars
UV	Ultraviolet
VF	Value factor
WFEN	Water-food-energy nexus



EXECUTIVE SUMMARY

This report shows that technical and economic decisions across the PV value chain are tightly coupled and must be managed as an integrated system, particularly for centralised (utility-scale) PV systems. The research addresses a fundamental challenge in the rapidly expanding solar industry: the complex interconnections between technical performance and economic outcomes that demand sophisticated decision-making approaches for large-scale solar PV, including key indicators for Agri PV as well as examples and case studies.

Key Findings

Decision Matrix Framework: The report introduces a comprehensive workflow mapping system that visualizes stakeholder interactions across the PV value chain—from banks and investors in development phases to O&M operators during operation. This framework reveals that quality gates implemented early in the value chain provide the greatest cost-effectiveness in preventing downstream failures, though significant gaps remain in stakeholder feedback loops.

Economic Impact of Quality Management: Case studies demonstrate that proactive quality management delivers measurable economic benefits far exceeding initial investment costs. Post-shipment testing with mobile laboratories can provide cost savings compared to stationary laboratory testing, while optimized planning and design review for rooftop installations can improve energy yield through better component selection and site assessment.

Application-Specific Strategies: Different PV applications require tailored approaches. Bifacial tracking systems, floating PV, and agrivoltaic installations each present unique challenges demanding specialized risk assessment and mitigation strategies. Geographic factors significantly influence operational approaches, with seasonal failure patterns requiring region-specific maintenance planning.

Climate Risk Management: The increasing frequency and severity of extreme weather events necessitates sophisticated risk assessment beyond traditional models. The report provides compelling evidence that proactive defensive strategies, including tracker stow protocols and appropriate module selection, can prevent catastrophic losses even during 1-in-500-year hail events.

Critical Recommendations

Early-Stage Quality Integration: Implement comprehensive quality gates during development and engineering phases where intervention costs are lowest. This includes mandatory technical due diligence, component testing protocols, and site-specific risk assessments.

Data-Driven Operations: Investment in monitoring systems and analytics platforms enables predictive maintenance and real-time optimization. The transition toward automated corrective and predictive maintenance represents a fundamental shift in asset management, with seasonal patterns highlighting the value of proactive resource planning.

Financial Model Evolution: Traditional financial models must incorporate climate-adjusted scenarios and account for fat-tailed distributions of extreme events. The introduction of Probable Maximum Loss and Average Annual Loss frameworks provides tools for quantifying risks, but these require updates reflecting changing environmental conditions. Grid constraints and



increasingly curtailment risks significantly affect project value and should be systematically considered from the earliest stages of both technical design and financial modelling.

Industry Impact

The frameworks, case studies, and best practices presented represent current industry knowledge but must be continuously updated to reflect technological advances, changing market conditions, and operational experience. The ultimate goal is creating a more resilient, efficient, and profitable solar industry capable of delivering sustainable, cost-effective renewable energy for decades to come.

This research provides essential guidance for stakeholders across the PV value chain, emphasizing that quality-driven decisions extend beyond individual projects to influence the bankability and public acceptance of solar PV technology. Overall, the study positions quality-driven, KPI-based and data-enabled decision-making as a central lever for ensuring that PV can reliably serve as a cornerstone of sustainable, secure and economically attractive energy systems worldwide.



1 INTRODUCTION

Quality in the solar PV sector is a complex and multifaceted topic that encompasses numerous initiatives, organisations, research institutions, and innovation projects involving multiple stakeholders distributed across a fragmented value chain. As the photovoltaic industry continues its exponential growth trajectory globally, the body of literature and guidance surrounding quality assurance continues to evolve rapidly, reflecting technological advances, market changes, and emerging best practices. This continuous evolution creates a clear and pressing need for regularly updated, comprehensive, and harmonized quality guidelines that reflect current industry standards and emerging challenges.

The fragmentation inherent in the PV value chain, spanning manufacturing, project development, installation, operations, and maintenance, creates significant complexity in quality assurance management. Unclear boundaries between stakeholders' responsibilities and specialized tasks, organisational siloing, the entry of newcomers to the market, and expansion into new geographic regions all contribute to increasing challenges in maintaining consistent quality standards across PV projects. Traditional quality frameworks, while valuable, often lack integration across these boundaries and fail to address the interconnected nature of technical and economic decision-making throughout a project's lifecycle.

Multiple quality guidelines and standards are currently available within the industry, often differentiated by stakeholder type, market segment, or application domain. However, a critical gap persists: the implementation of these guidelines is rarely mandated or systematically enforced across the value chain, limiting their real-world effectiveness and impact. This implementation gap represents a significant barrier to achieving consistent quality improvements across the industry and maximizing the economic performance of PV systems.

This report addresses a fundamental challenge identified by the authors: the absence of a clear, validated, and comprehensive mapping of the workflow, terminology, relationships, and interactions between stakeholders along the entire PV value chain. Without such a framework, communication barriers persist, best practices remain siloed, and opportunities for optimization are missed. The development of a structured ontology to establish a common industry language is therefore essential for aligning diverse stakeholders around shared quality objectives.

Mapping and visualizing the complete value chain workflow represents a critical first step toward industry consensus on standardized approaches to high-quality PV project development and delivery. This systematic mapping enables multiple strategic benefits: i) identification of state-of-the-art practices and opportunities for advancement beyond current standards, ii) recognition of critical decision points that significantly impact project profitability and long-term performance, iii) identification of quality gates and control points where cost-effective quality improvements can be implemented, and iv) provision of a structured framework that organisations can adopt to optimize their internal processes and ensure alignment with industry best practices.

The frameworks, decision matrices, and case studies presented in this report build upon this foundational mapping to demonstrate how strategic operational and management decisions - from design phase through operations and maintenance - directly influence both technical reliability and economic returns on investment. By connecting quality decisions to measurable economic outcomes, this report provides stakeholders with the evidence-based insights needed to justify investments in quality assurance and make informed strategic choices throughout the PV project lifecycle.



2 DEFINITION OF PERFORMANCE AND ECONOMIC KPIS

2.1 Introduction

This report is intimately tied to the IEA PVPS Task 13 Report “Technical Key Performance Indicators for Photovoltaic Systems: Challenges and Best Practices” [1], where the most important technical, economic, and sustainability key performance indicators (KPIs) and methods to calculate these are described. This report focuses on the next step: what decisions are — or can be — made based on technical and economic KPIs, how these decisions impact economic KPIs, and how they can contribute to a standardized terminology in the PV community and industry.

Decision-making plays a vital role in the operational performance and health of the PV asset and, as shown in Figure 1, involves an interlink between technical and economic KPIs. For example, the asset owner or its approved representative (e.g. the O&M provider) must decide which actions to take to maximize the yield of the plant, whilst evaluating their cost-effectiveness. The asset owner and its representative must search for the optimal and cost-effective solution for that specific PV plant, considering its physical environment, weather, climate, and other asset metadata, as well as its economic circumstances. Asset owners and its representatives have a plethora of options and interventions to choose from, which are in many cases site-, technology- or region-specific. Hence, while a “one-size-fits-all” philosophy is rarely appropriate, PV plants are often installed in locations with similar climatic conditions, grid and market rules. This allows for the generalization of lessons learned, enabling the PV plant operator or owner to apply such lessons to the system under consideration.

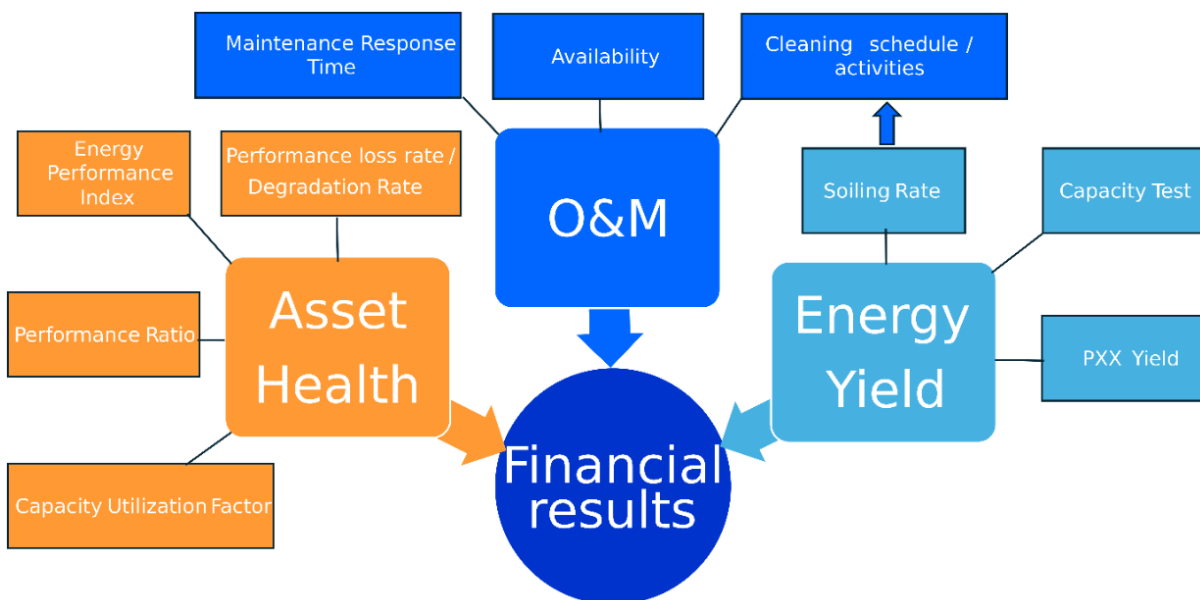


Figure 1: The interlinked nature of technical and economic KPIs, from [2]

In most cases, technical performance directly affects economic performance, whereas in others, effects are iterative. For example, the modelled yield of a plant is highest when PV modules are clean (or not soiled), yet cleaning itself has an economic cost (labour, materials) and may also result in additional wear and tear of the PV modules (e.g. brushes scratching the glass, reducing its ability to capture sunlight, degradation of antireflective coating). In low-



soiling environments, cleaning modules on a daily basis is clearly not a cost-effective strategy, while high-soiling environments may require either daily cleaning, or a corrective/predictive cleaning protocol with the necessary resources available – this is discussed in more detail in section 4.3. If a plant is subject to strong curtailment throughout the day and year, it may be that soiling is seen as less important than ensuring that all components are operational, even though soiling may mask or cause other performance issues. This may require staff and spares to be on hand to address any problem that may arise and thus have sufficiently high availability of the plant.

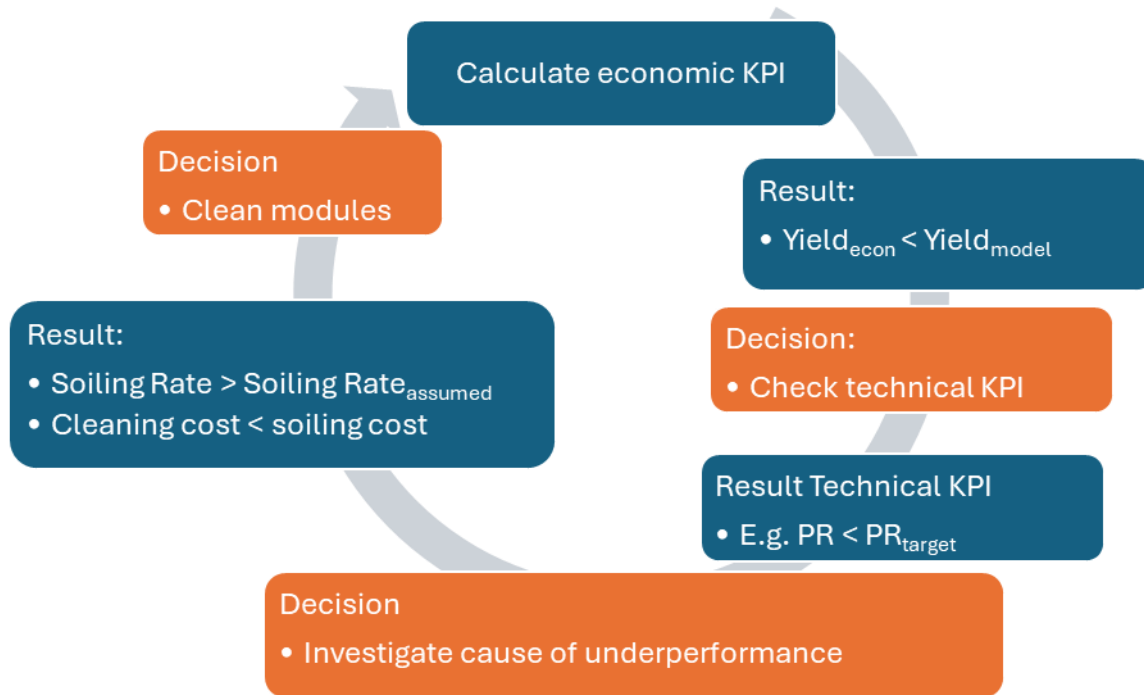


Figure 2: Example high-level iterative process, starting from the economic KPI calculation and evaluation. Decision steps are often evaluated for cost-effectiveness.

With both technical and financial KPIs being discussed here, there is a strong, industry-wide, need to develop an ontology to enable easy human and machine-readable forms of interactions among value chain participants. As one sees from Figure 2, the nature of these interactions involves both human and machine (computer) interactions. Fortunately, this ontological work is advancing from the original efforts that established the Orange Button PV Taxonomy as an OpenAPI taxonomy to streamline contracting and financial interactions in the PV value chain [3]. The IEA PVPS Report “Digitalisation and Digital Twins in Photovoltaic Systems” focuses [4], among other things, on the role and development of data models and ontologies for PV digitalization to streamline value chain interactions of technical and economic KPIs. For example, the PV module subdomain ontology in Figure 3 is connected to site, cells, battery, exposure and charge controller ontologies. These PV ontologies are modular and interoperable, and part of the Materials Data Science Ontology (MDS-Onto) [5]. MDS-Onto is being developed as an open-source project, providing tools for people to propose new terms and relationships to be incorporated into MDS-Onto, and tools for FAIRifying and standardizing PV vocabularies. Community members are beginning to add the KPIs and their relationships into MDS-Onto, thereby streamlining the process and increasing the availability of efforts like those presented in this report. By establishing common ontologies, the PV industry can achieve more consistent energy yield assessments, define clearer contractual KPIs, and reduce ambiguity in performance guarantees for asset owners and investors.



2.2.1 Methods to determine degradation and failure KPIs during operation

All the KPIs mentioned in Table 1 have specific methods and requirements for measuring them. In terms of needed data, the KPIs roughly fall into several categories: those that require (long-term) data on the electrical performance of the PV system under consideration, at different levels of detail (module, string, inverter, system), and those that require data from component testing and field inspection and detailed and standardized logging of the results, along the PV system value chain, but mainly during the operational phase.

Table 1: Overview of KPIs related to performance loss, degradation and failure.

KPI	Description	Applies to	Measured by
PLR	Performance Loss Rate, describing the evolution of a system performance KPI like PR in %/year	System, string, module	Several methods to determine long-term trend in performance KPI like PR [6]
Rd	Module degradation rate, describing the evolution of module performance in %/year	Modules	As PLR, but on the module level, and excluding reversible losses such as soiling.
TXX	Txx, commonly the T80, increasingly also T85 or T90, the lifetime until a module is degraded to 80%, 85% or 90% of its initial performance. Manufacturers typically provide Txx values of up to 30-35 years.	Modules	Most commonly: based on accelerated ageing tests. Alternatively: from outdoor measurements until Txx is reached.
Downtime	Downtime, of system, inverter or tracker, to be used to calculate technical, contractual, or energy-based availability of systems, inverters, trackers [7].	System, inverters, trackers	Measurement of time the system, inverter or tracker is not operating as expected.
MTBF	Mean Time Between Failures: A reliability metric that gives the average time between system or component failure during operation.	System, components	Detailed digital logging of component failures with standardized nomenclature during operational time
Annual Failure Rate	For each component type: the percentage of components showing failures in a 12-month period.	Components	As above, but considering only the failures occurring in the selected 12-month-period
First Year Failure Rate	Quality KPI measuring the percentage of failures of each component type in the first year of operation, including issues due to manufacturing, transport, and installation.	Components	As above, additionally from warranty claims, field inspection during EPC operation
Manufacturing Defects Rate	Quantifies the defect rate of components coming from the manufacturer measured during quality control	Components	Quality Assurance and Quality Control. Flash testing / EL inspection for modules.
Transportation Damage Rate	Quantifies the number of defects in components due to transportation and logistics operations.	Components	As above, additionally packaging integrity inspection
Installation-related Failure Rate	Quantifies the number of defects originating from their installation in the field.	Components	As built/in field testing after installation using performance measurements, visual, IR, EL inspection.



For determining Rd and PLR there are certain requirements in terms of input data needed, like system and module-level performance data, and sometimes intermediate KPIs like PR or Energy Performance Index (EPI) that are used as metrics that exhibit the PLR or Rd and are affected by an interaction of degradation, failure and soiling. Previous research conducted in the framework of the IEA PVPS Task 13 has focused on comparing methods to determine the PLR. The general approach is to, after preprocessing and filtering the data, determine the long-term trend in performance of a performance metric of choice (PR, EPI, power, etc), and to derive the annual PLR value from this long-term performance trend [6].

A substantial number of different methods to determine the PLR was compared, for more details please refer to the work of French et al [6]. To determine the Txx metric shown in Table 1, which is usually determined at the module level, the STC power of the module under test is determined at regular intervals using indoor testing equipment and standardized procedures. The procedure is repeated until the STC power drops below the specified Txx level.

For the KPIs regarding the failure rates in PV systems, very different data are required. To determine downtime, the O&M monitoring platform needs to be set up with conditions that define whether a system or a component of it is operational or experiencing downtime. Continuous tracking then allows the asset manager to determine the downtime at system or component level. The conditional rules that define downtime can be defined contractually (for contractual downtime) or based on technical characteristics (technical downtime).

To determine component failure rates such as annual failure rate and first-year failure rate, and related KPIs such as the mean time between failures (MTBF), detailed tracking of failures at the component level is required, using a O&M ticketing and asset management platform. For the validity of the KPIs it is important that all failure data from the field is collected in a standardised and digitalised manner. To determine failure rates that predate the O&M phase, e.g. manufacturing defects rates, transportation damage rates and installation-related failure rates, comprehensive inspections and standardised data collection are necessary along the PV system value chain.

2.3 Energy Losses and Repair Costs

2.3.1 Energy losses

Energy losses are the most important output factor that asset owners care about, as energy production drives revenue generation. Depending on the role and interest of the stakeholder, a variety of KPIs are used, typically distinguishing between avoidable (e.g. energy losses due to tracker misalignment, soiling-induced energy losses, or fuse replacements), and unavoidable (e.g. efficiency changes due to climatic conditions, technical curtailment, grid unavailability). Unavoidable energy losses are design or technology choice consequences, or aspects outside of the control of the asset owner and its representatives, whereas avoidable energy losses may be avoided through appropriate O&M actions.

KPIs for energy production and losses can be expressed in absolute terms (e.g. MWh), yet comparability between sites and geographies is typically aided by expressing such KPIs scaled to nameplate power (e.g. relative yield, kWh/kW/year), as well as scaling to incident insolation (i.e. the normalised efficiency (η_N , power) [8] or Performance Ratio (PR, energy) [9]).

Energy losses are intimately tied to data availability and modelled performance of PV power plants. PV systems where only a portion suffers downtime can reasonably easily be modelled or extrapolated based on data from comparable arrays or inverters on-site. When full systems



suffer outages, more advanced imputation techniques must be employed to re-create the data or fill in data gaps, to then model the system performance and associated energy losses [10], [11].

Similar to the management and tracking paradigm of traditional generators, detailed accounting of energy from the fuel input to the saleable electricity output is often required. As PV systems are directly influenced by weather conditions, as well as how they are operated (curtailed or not), measuring the necessary data at the appropriate resolution and using high-quality sensors according to IEC 61724-1 is fundamental [9]. Moreover, this also means that data must be of high quality, with appropriate imputation techniques used, and transparency throughout to ensure that the resulting KPIs are correctly calculated [1]. The most important KPI that is then calculated is the Performance Ratio (PR), occasionally with data- or weather-related corrections (e.g. to exclude data outages). Of note, contiguous data losses (i.e. multiple hours or days in a row of no data) can lead to significant deviations in the calculated PR, which are also affected by the local geography (mountains versus plains) [2]. When data and/or full system outages occur, energy production and possible energy losses have to be quantified, for which a variety of models and techniques exist [1].

Photon-to-electron performance models from O&M providers and asset managers vary in their level of detail, and the sequence in which “losses” are attributed. In practice, such models fall in the category of “digital models” or “digital shadows”, using the definition of [12]. Using such models, it then becomes possible to compare measured/observed performance and compare this to the expected performance. The Energy Performance Index (EPI) is then the ratio of the measured yield to the expected yield, using such a model. Consequently, the quality of the model, choices of model coefficients, and the input data used can have a meaningful impact on the resulting calculation of the EPI. When implemented with care, the EPI can provide more information to asset owners and O&M providers than the PR [2].

An often-used KPI is the capture price (€/MWh), which is the volume-weighted price of a generator, typically calculated on an hourly basis (or shorter, depending on the market), as given in Eq. (1):

$$\text{Capture price} = \frac{\sum E_i * p_i}{\sum E_i} \quad (1)$$

Where E_i is the energy output to the grid in that interval and p_i the price of electricity sold in that interval. PV power plants with long-term energy offtake contracts for 100% of the produced energy, such as Power Purchase Agreement (PPA) see little to no variability in the capture price. As PV power plants become increasingly exposed to spot market prices (“merchant operation”), their income becomes less predictable. Over time, as more PV and wind generators enter a market, self-cannibalisation becomes an issue, seen in declines in capture prices, as more generation occurs at the same time, while demand patterns are not yet shifting at the same rate [13], [14], [15].

The importance of energy losses varies according to the season, time of day, as well as the amount of curtailment that the generator experiences (or would have experienced).

The most important KPIs are summarised in Table 2. An overview of most technical KPIs can be found in [1], while [16] contains O&M-related KPIs.



Table 2 : Main KPIs used for energy loss estimations

KPI	Description	Obtained or measured by
Energy yield (absolute or relative) [MWh] or [kWh/kW]	Base KPI for subsequent KPIs. Losses require a model (or multiple models). The (expected) PR is often a necessary additional KPI calculated to determine losses or deviations in performance.	$E_{loss} = E_{measured} - E_{expected}$
PR [%]	Most-used KPI translates reasonably well between sites and geographies. The PR can be de-scaled to obtain absolute values of energy and plane-of-array irradiation.	$PR = \frac{E/P_{STC}}{H/G_{STC}} = \frac{\sum P/P_{STC}}{\sum G/G_{STC}}$
EPI [%]	Model-based evaluation of system performance, using measured weather inputs. Model coefficients and data must be carefully selected and curated.	$EPI = \frac{E_{meas}}{E_{expect}} = \frac{\sum P_{measured}}{\sum P_{expected}}$
Capture price [€/MWh]	Volume-weighted average price of generated energy.	$Capture\ price = \frac{\sum E_i * p_i}{\sum E_i}$

2.3.2 Cost effectiveness of reuse and repair

Optimizing end-of-life (EoL) management strategies is becoming increasingly critical in PV O&M, not only to enhance PV reuse readiness but also to ensure bankability of the PV repair/reuse paths. Understanding and addressing economic KPIs is essential for assessing the financial impact of decisions related to PV repair/reuse. As indicated in [17], certain factors should be taken into account in assessing both technical and economic bankability of transitioning from PV O&M to “preparation for reuse” [18]:

1. *Addressable Volume and Testing/Repair Costs.* The scale of reusable PV modules and the expenses associated with functionality testing and repair are pivotal in determining the profitability and financial feasibility of the PV reuse market. Decisions on triage, qualification, and repair strategies directly affect these costs, shaping the overall economic feasibility of second-life PV.
2. *Reliability, Safety, and Residual Efficiency.* The post-repair performance of reused PV modules directly impacts investor and buyer confidence. Higher reliability and efficiency translate into stronger market acceptance, influencing both pricing models and long-term economic returns.

The decision to repair rather than replace and recycle/dispose depends on multiple factors, primarily the cost of repair per kW and the cost-benefit ratio of repair versus replacement. According to NREL's study [19], if the cost of repair approaches or exceeds a significant percentage of a new component's price, replacement may be the more viable option. However, repairs can extend the operational lifetime of components, leading to long-term savings. Besides, recent research by CIRCUSOL and IEA PVPS Task 13 experts [20] indicates that with optimized repair strategies, up to 50% of PV waste can be diverted from recycling into reuse, significantly reducing lifecycle costs.



Testing plays a crucial role in determining whether a PV module or component should be repaired or reused. While testing incurs (a major part of) costs, it helps avoid unnecessary replacements, ensuring that only viable components remain in operation. SolarPower Europe and SUPERNOVA experts [20] emphasize the importance of streamlined triage frameworks to ensure cost-efficient qualification methods for reuse. However, testing also introduces temporary downtime, leading to energy losses that need to be considered. The accuracy of testing methods is critical to ensuring that repairable modules are correctly identified, as misclassification could lead to unnecessary expenses or premature failures.

The reliability of repaired components is another key economic factor. A high failure recurrence rate after repair suggests that repairs are not durable, reducing the financial justification for such interventions. Conversely, if repairs significantly extend the component's lifetime, they can provide substantial cost savings, particularly when compared to new procurement. PV Module Reliability Scorecards, such as those proposed by DNV or Kiwa/PVEL provide industry-wide insights into failure recurrence trends, helping asset managers make informed decisions. Evaluating the resale value of reused modules also provides insight into whether a secondary market for tested components can offer financial benefits. According to recent research [21], [22], it becomes evident that resale values of second-life modules do vary but may provide a viable cost-saving opportunity in certain markets. Research by Tsanakas et al. [20] suggests that second-life PV modules can retain between 50% and 80% of their original market value, depending on the level of degradation and re-qualification, in terms of residual performance and safety, respectively.

Beyond individual cost considerations, the broader financial impact of PV repairs/reuse on the PV system's lifecycle cost must be assessed. Savings from repair and reuse strategies can influence the levelized cost of electricity (LCOE), a crucial metric for assessing long-term project viability. Studies have shown that integrating reuse strategies can reduce LCOE in scenarios where the extended module lifetime offsets testing and repair costs. If repair and reuse lower overall system costs without significantly compromising energy yield, they contribute to a more financially sustainable and circular approach to PV asset management. The CIRCUSOL Project has also proposed a Product-Service System (PSS) model for PV reuse, which could shift the economic model toward leasing and service-based ownership structures, further improving financial feasibility.

For most of the listed KPIs and associated activities in **Table 3**, personnel costs – which play a significant role in budgeting – were unfortunately not disclosed by any of our sources. Given the relative infancy of this market, the available cost figures, while reported within the past three years, remain market-specific and incomplete. As a result, they should be regarded as indicative rather than definitive and may be subject to variation.

Furthermore, to establish sustainable business models for PV module reuse and strengthen the viability of a successful reuse market – particularly in light of the currently low prices of new PV modules – policy interventions should focus on preventing the premature disposal of functional modules due solely to their short financial life [20]. In this regard, in their recent study, Tsanakas et al. [20] advocate for policies that mandate a state-of-health (SOH) assessment for PV modules that reach the end of their first life at least ten years before the expiration of their warranty. For instance, for modules with a 30-year warranty, an SOH check should be required if repowering or revamping is planned for 20 years of operation. We anticipate that such a policy could become relevant and enforceable by 2030. By that time, standardized procedures for performance and safety checks in PV reuse will be well established, and their costs will be integrated into the planning phase, OPEX, and asset management budgets of PV projects.



Table 3: Overview of KPIs related to PV repair/reuse and testing for repair/reuse.

KPI	Description	Applies to	Measured by
Repair Cost per kW	Average cost of repair per kW of PV capacity.	Modules, inverters, trackers, components, personnel	Total repair cost divided by the affected capacity
Testing Cost per kW	Cost associated with testing (pre-evaluation and triage of) modules for repair or reuse per kW. Includes also certified quality testing by 3 rd party.	Modules, strings	Testing expenses per unit capacity (e.g., EL, IV curve, flash testing, visual inspection, R _{iso} test)
Packaging materials Cost per unit / kg / m	Cost associated with packaging materials for transportation from/to decommissioning, testing or re-commissioning sites.	Modules	Packaging expenses per unit (for pallets and cardboard boxes), weight (for cardboard/cellular rubber) or length (stretch wrap)
Logistics cost per km	Cost associated with transportation from/ to decommissioning, testing or re-commissioning sites.	Modules	Transportation (fuel or electricity) expenses per distance covered
Cost-Benefit Ratio of Repair vs. Replacement	Compares the cost of repairing a component to the cost of replacing it.	Modules, inverters	Ratio of repair cost to new component cost. A lower ratio indicates cost-effectiveness
Failure Recurrence Rate After Repair	Percentage of repaired components that fail again within a defined period.	Modules, inverters, BOS components	Field monitoring, warranty claims, maintenance logs
Energy Loss Due to Testing Downtime	Quantifies the energy lost while modules are out of operation for testing.	Modules, system	(Downtime hours × expected generation) / total capacity
Expected Lifetime Extension After Repair	Additional years of operation gained through repair compared to replacement.	Modules, inverters	Accelerated aging tests, field performance monitoring
Testing Accuracy Rate	Percentage of tested modules correctly identified as repairable or reusable.	Modules	Comparison of test results with long-term performance data
Resale (Residual) Value of Reused Modules	Market value of modules after reuse compared to new modules.	Modules	Market data, auction platforms, resale transactions
Cost Savings from Reuse vs. New Procurement	Savings realized by using tested reusable modules instead of new ones.	Modules, BOS	(New module cost - reused module cost) × installed capacity
Impact on LCOE (Levelized Cost of Electricity)	Change in LCOE due to repair and reuse strategies.	System	(Total lifetime costs with repair & reuse) / (Total energy generated)

2.4 KPIs for Agrivoltaics

KPIs in agrivoltaic (AV) systems consider factors that are often overlooked in conventional ground-mounted photovoltaic (CGMPV) systems. Typically, the layout of CGMPV systems is defined by minimizing the LCOE [23] or, maximizing the net present value (NPV) or similar profitability indexes [24]. In contrast, the coexistence of agricultural and energy conversion activities necessitates the use of KPIs that assess the performance of AV systems not only in terms of energy conversion but also regarding crop yield, land use efficiency, water savings,



and economic performance. Additionally, current legislation on AV systems may impose restrictions on specific KPIs, such as reductions in ground irradiation or crop yield when compared to open-field conditions [25]. The report titled “Dual Land Use for Agriculture and Solar Power Production: Overview and Performance of Agrivoltaic Systems” [26] by IEA PVPS Task 13 provides a comprehensive overview of AV KPIs. It summarizes the most common electrical, agricultural, economic, and environmental KPIs. This section offers further details and context on some of the most widely used KPIs, introduces integrated KPIs, and discusses biodiversity and landscape impact KPIs.

The ground coverage ratio is defined as the ratio between the total surface PV area of the AV system (A_{pv}) and the total surface area occupied by the AV system (A_{apv}) and is defined by the following equation:

$$GCR = \frac{A_{pv}}{A_{apv}}$$

It is a commonly used KPI to provide info concerning the density of a PV system (i.e., MW_p/ha) and to compare CGMPV systems to AV [27], since the latter is marked out by lower density for balancing crop production and food production. It can also be expressed as the ratio between the PV collector length and the row pitch [28]. The GCR is used as a proxy for the solar irradiation reduction on ground on metanalysis linking AV systems geometries to crop yield reduction [25].

The land equivalent ratio (LER) is a KPI typically used in agroforestry or intercropping systems to analyse the land use efficiency between sole cropping and combined cropping systems [29]. In AV systems it quantifies the land use efficiency as compared to using the land only for agriculture or PV electricity production through CGMPV systems. It is defined as the summation of the crop ratio (CR) and energy ratio (ER) as follows [30]:

$$LER = CR + ER = \frac{Y_{crop,apv}}{Y_{crop,monoculture}} + \frac{Y_{electricity,apv}}{Y_{electricity,pv}}$$

Where, $Y_{crop,apv}$ is the agricultural yield in the APV system (kg/ha), $Y_{crop,monoculture}$ is the agricultural yield in open field condition, $Y_{electricity,apv}$ is the electricity yield from the APV system, $Y_{electricity,pv}$ is the electricity yield from an optimized CGMPV system. $Y_{crop,apv}$ should take into consideration the unavoidable land losses due to the supporting structures [31]. A LER greater than 1 indicates increased productivity of dual land use as compared to sole agriculture or PV production through CGMPV system. For example, a LER equal to 1.5 means that a 1-hectare (ha) AV system would produce as many crops and electricity as 1.5 ha of mono productions. Although the LER is a commonly used KPI in AV research to evaluate the land use efficiency of AV systems, it has been demonstrated that it cannot be used as an objective function for AV system optimal design [31]. If the LER is used as objective function to be maximized, it can lead to unfeasible AV system configurations that can lead to unprofitable agricultural, and electricity yields per ha in favour of the land use efficiency.

While the LCOE is commonly used KPI for optimizing the layout of CGMPV systems, the main drawback is that it does not consider the agricultural aspects of AV systems. To remedy this shortcoming, Trommsdorff et al. (2023) [32] proposed the levelized cost of agricultural products, specifically apples. Another commonly used economic KPI for AV systems is the NPV, or derived KPI like the internal rate of return (IRR), that factors costs and revenues of both agricultural and electricity production. Closely connected to the NPV and profitability aspects is the concept of AV contribution margin. To adopt AV system, the annual profit generated from PV and the agricultural contribution margin under AV system should be larger than the base



agricultural contribution margin [33]. While the NPV and contribution margin factors both agricultural and electricity profits, the use of these KPIs might not be used in a straightforward way for the optimization of AV systems because typically the revenue generated by agricultural activities can be significantly lower than those generated by electricity sale [34], [35]. To remedy these issues, specific technical or crop-centric KPIs are used such as the CR, or simply the crop yield, the water use efficiency, or the light reduction can be used to assess or maximize crop production.

Environmental KPIs can consider issues concerning material use, CO₂ emissions, or other impact categories KPIs [36]. Environmental aspects in AV systems are pivotal, especially for the comparison with CGMPV system since, given the fact that supporting structures typically require a higher volume of materials. The environmental challenges of AV systems can be undertaken through innovative actions concerning system configurations and materials components.

Since AV systems provide benefits across the water-food-energy nexus (WFEN), it is of interest to study integrated WFEN indexes like the one developed by El-Gafy [37]:

$$WFEN\ index = \sum_{i=1}^N w_i X_i$$

Where, w_i is the weight given to each N-th KPI, N is the KPIs number, and X_i is the normalized KPI. An example of integrated WFEN KPI (KPI_{WFEN}) can be as follows:

$$KPI_{WFEN} = w_{water} KPI_{norm,water} + w_{food} KPI_{norm,food} + w_{energy} KPI_{norm,energy}$$

where, w_{water} is the weight corresponding to the normalized KPI of the water dimension ($KPI_{norm,water}$), w_{food} is the weight corresponding to the normalized KPI of the food dimension ($KPI_{norm,food}$), w_{energy} is the weight corresponding to the normalized KPI of the energy dimension ($KPI_{norm,energy}$). The weights can be assigned through multi criteria decision making weighting techniques [38]. Integrated KPIs can be used for holistic optimal design of AV systems [39].

AV systems result in a loss of agricultural land due to the supporting structures of PV modules, which restrict agricultural machinery from approaching closely because of associated risks. This land loss is typically around 10% [31]. While this represents an economic loss for agricultural productivity, it often serves as a forced source of biodiversity. Therefore, biodiversity KPIs such as species richness and abundance, and the presence and diversity of pollinators can be employed to assess the biodiversity impacts of AV systems [40], [41].

Another critical set of KPIs for AV systems relates to their landscape impacts. Landscape impact is one of the major factors influencing social acceptance of commercially viable PV systems and is often a significant hurdle in the permitting process [42]. In contrast to CGMPV systems that optimize land use with a standard spatial layout, AV systems offer more flexibility by integrating PV with various crops, adjusting PV module densities, and modifying the structures. This adaptability has the potential to lessen landscape impact and enhance public acceptance. Sirnik et al. (2024) [43] provided a set of KPIs for evaluating landscape changes associated with AV systems, including land use changes, crop alterations, the presence of vertical non-agricultural vegetation, and the characteristics of AV system structures. Additionally, Biró-Varga et al. (2024) [44] developed landscape quality factors to evaluate the experience and quality of different landscapes.



2.5 Mitigation Strategies

Specific mitigation strategies can be implemented to limit the occurrence and/or the magnitude of PV performance losses. These are typically categorized as preventive or corrective actions, which can be further refined, depending on the system or component and the range of available mitigation strategies. (See Figure 4, which identifies mitigation options for soiling).

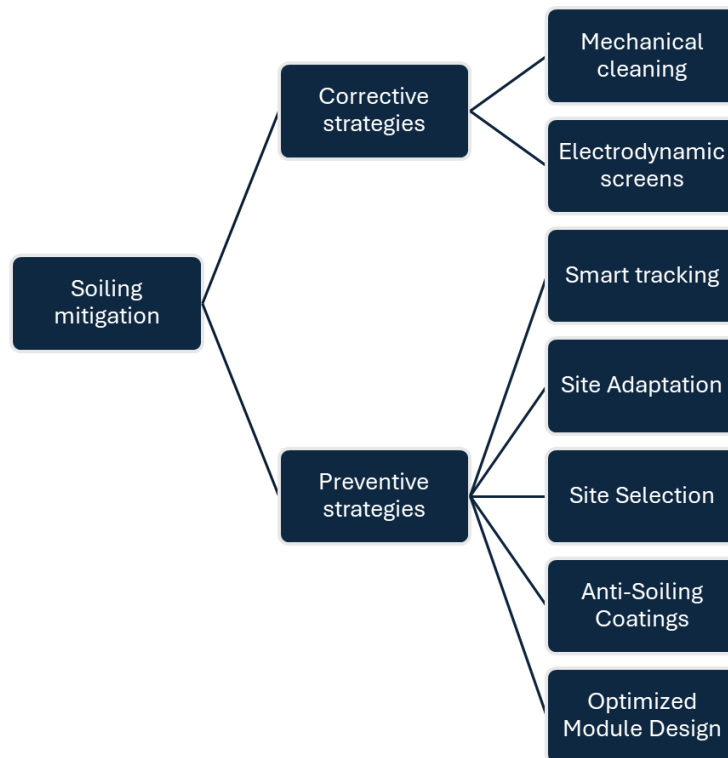


Figure 4: Corrective and preventive mitigation strategies to address soiling losses in PV systems. Adapted from Bessa et al. (2021).

Preventive actions: Preventive actions, which can be either passive or active, aim to minimize the likelihood of performance losses occurring in the first place but can also reduce their impact if they occur. For example, **passive strategies** to minimize soiling include the application of coatings that inhibit accumulated soiling and/or the reduction in airborne dust via site selection or onsite vegetation management. **Active strategies** for mitigating soiling losses include washing or brushing dust from modules without a trigger (i.e., before a critical soiling level is achieved).

For losses attributable to other factors, such as partial shading from overgrown vegetation or storm-induced damages, different preventative strategies apply. Regularly scheduled mowings and site inspections can keep a site clear of unwanted vegetation. Additionally, investing in more robust system designs - from modules to fasteners to racking - can significantly reduce performance losses resulting from high winds.

Preventive actions require a higher initial investment but typically have low to no ongoing operating costs. Corrective actions, on the other hand, address performance losses after they have occurred.

Corrective actions: Cleaning heavily soiled PV panels illustrates some of the complexities underlying the decision-making behind preventive vs corrective actions. One way to reduce ongoing cleaning costs might be to purchase and install cleaning robots, although this strategy



requires a sizeable upfront investment and may lead to additional costs, such as maintenance of the robots or unexpected failures. The alternative-cleanings performed by the local O&M team or a third party-- require no upfront investment but incur ongoing costs for water, labour and the staging of equipment over the life of the system.

Predictive maintenance strategies can also be performed to anticipate, based on data analysis, the occurrence of losses before they occur, optimizing both efficiency and costs.

Consider the example of a PV plant's electrical network. The gold standard for preventative maintenance involves periodically infrared (IR) imaging a subset of PV connectors (both module-to-module and string-to-string) to look for evidence of high resistance. The alternative--corrective action--would only be executed once problems emerge, such as melted connectors and arc faults. Although the connectors need replacement under both scenarios, under the corrective strategy, damage could extend beyond the connectors, involving modules and other components, and potentially trigger onsite and offsite fires, resulting in expensive safety reviews and lawsuits. Moreover, the system could be shut off for extended periods, leading to significant generation losses.

However, one possible benefit of corrective action—depending on the component and performance metric—is the prospective opportunity to enact lessons learned by replacing original parts with more robust ones. One example would be swapping out threaded bolts, which have high failure rates, with locked bolts, after the threaded bolts fail.

Decision-Making Considerations: Deciding between preventive and corrective actions, or a combination of both, is typically based first on a technical feasibility assessment and subsequently on the evaluation of the economic KPIs. “One-size-fits-all” solutions do not exist, as the feasibility of mitigation strategies depends on the technology and its performance metric as well as on geographic, or logistical constraints. For example, the use of water for cleaning in arid and desertic regions may not be practical, necessitating alternative solutions such as dry-cleaning or anti-soiling coatings. Or, in the case of fastener O&M, the identification of early failure indicators (micro-cracks, bolt loosening, etc.) might be a preventative strategy that leads to corrective action. Similarly, performing O&M visits to remote sites may be challenging, increasing reliance on automated or preventive systems.

The final choice of mitigation strategy must consider its impact on the economic KPIs. The selected strategy, indeed, must guarantee the best tradeoff between costs and long-term revenues. Overinvesting in prevention strategies might increase initial costs, whereas relying too heavily on corrective actions could result in too frequent interruptions, higher operational expenditures and potential safety and legal issues.

In summary, preventive actions often require higher upfront investments but result in lower ongoing maintenance costs and operational disruptions. Conversely, corrective actions typically involve lower initial investments but higher ongoing and potentially indirect costs.

Conclusion: An optimal mitigation strategy should maximize the difference between generated revenues and additional costs. These calculations must be specific to the site, its operational requirements, the uncertainty associated with each mitigation strategy, the available resources and the owner's financial goals.



2.6 Financial Probable Max Loss and Average Annual Loss

Insurance policies for large-scale PV power plants or portfolios of PV assets are renewed and negotiated annually. As a result, large insured losses incurred over a relatively short period of time are capable of dramatically resetting the insurance market.

The increasing frequency and severity of extreme weather events is a proven trigger for insurance market entrenchment. This market dynamic is important to understand as solar project owners, investors, financiers, and lenders use insurance to transfer risk to insurers.

In a soft insurance market environment, project stakeholders can transfer significant levels of risk to insurers at relatively low rates. In a hard insurance market environment, these stakeholders can experience increased insurance premiums and deductibles and policy terms with restrictive sub limits that cap risk transfer based on specific perils. Entering 2025, the global renewable energy insurance market is experiencing a hard market cycle that has negatively impacted project viability in some regions.

Access to insurance is critically important to global efforts to mitigate climate risks. On the one hand, sustained and widespread solar development is required to avert a global climate crisis. On the other hand, solar development activities rely upon access to capital, which in turn relies upon access to insurance, the availability of which is directly impacted by financial losses due to extreme weather events.

Given the solar industry's reliance on a sustainable insurance ecosystem, it is important to understand how insurers use natural catastrophe models to evaluate weather risk. Starting from a stochastic event data set for each peril, a typical catastrophe model simulates tens of thousands of hypothetical events. This analysis yields locational intelligence regarding loss event severity and frequency. Key model outputs include probabilistic financial loss estimates that inform insurance availability, pricing, and terms.

2.6.1 Probable maximum loss

Probable maximum loss (PML) is the estimated value of the largest financial loss an insurer is likely to incur on a policy based on a specific hazard or natural catastrophe peril, assuming the proper operation of engineering safeguards. Insurers use PML estimates to optimize coverage pricing, terms, and sublimit. PML estimates are often based on 1-in-500-year event severity assumptions. Traditional all-risk insurance policies typically include sublimit for natural catastrophe perils (e.g., earthquakes, hurricanes, and floods) and increasingly for severe convective storms (e.g., hail and tornadoes) and wildfires. Asset owners can use PML estimates to understand risk exposure, make informed risk management decisions, and address insurability concerns during project planning.

2.6.2 Average annual loss

Average annual loss (AAL) is the estimated value of the financial loss that an insurer expects to incur on average each year. AAL is derived by modelling peril-specific catastrophe scenarios to determine event probability and severity over a long period of time and averaging expected losses on a per annum basis. Insurers use AAL estimates to price policies and set deductible amounts, evaluate portfolio level risk exposure, and optimize reinsurance levels. Asset owners can use AAL estimates to manage risk, make informed coverage decisions, and account for financial exposure outside of insurance in pro forma models.



2.6.3 Climate change and evolving risk models

As climate change accelerates, the frequency and severity of extreme weather events are increasing beyond historical patterns, leading to greater unpredictability in solar project risks. In “The (Mis)behaviour of Markets”, Benoît Mandelbrot demonstrated that extreme events in financial systems follow fractal, heavy-tailed distributions rather than the Gaussian assumptions commonly used in insurance models. The same principle applies to climate-related risks, where hurricanes, hailstorms, wildfires, and floods are not independent or randomly distributed but instead cluster, forming fat-tailed risk distributions. This means that catastrophic losses occur more frequently than traditional models predict, leading to higher-than-expected losses for insurers and asset owners. As a result, the global reinsurance market absorbs the largest share of extreme loss exposure and has tightened considerably, raising premiums and reducing coverage for renewable energy projects. If probable maximum loss and average annual loss calculations fail to account for these fractal risk patterns, insurers and investors may significantly underestimate their exposure. This can lead to unexpected financial shortfalls and project viability risks. It is therefore essential for financial models to integrate climate-adjusted risk scenarios that reflect the increasing volatility of solar asset performance and insurance markets.

2.6.4 Volcanic eruptions and solar resource risk

Beyond weather-related risks, large-scale volcanic eruptions pose a distinct but equally underestimated threat to PV assets. Historical events such as Mount Pinatubo in 1991 and Tambora in 1815 injected massive amounts of sulphate aerosols into the stratosphere, reducing global solar irradiance by up to five to fifteen percent for one to three years. This phenomenon, known as volcanic-induced solar dimming, follows power-law distributions, meaning that severe but infrequent eruptions occur more often than Gaussian models predict. Yet, despite this well-documented impact on solar resource availability, volcanic dimming is rarely considered in PV insurance models or project finance assessments. The implications for long-term solar energy production, power purchase agreements, and financial returns could be significant, particularly in regions that rely heavily on solar generation. Given the difficulty of integrating such rare but extreme risks into traditional insurance frameworks, parametric insurance solutions based on atmospheric optical depth thresholds could help mitigate financial losses from prolonged irradiance reductions. Furthermore, stress-testing PV financial models under scenarios of volcanic-induced solar dimming would provide a more resilient approach to long-term energy planning and investment strategies.

2.6.5 The need for industry-wide investigation and solutions

As the solar industry continues to expand, it must confront not only the immediate risks posed by extreme weather but also the less frequent yet potentially devastating effects of volcanic-induced solar dimming. The increasing unpredictability of climate patterns and the non-Gaussian nature of these risks call for a reassessment of existing insurance models and financial projections. Addressing these challenges requires a more comprehensive approach that includes improved risk modelling, climate-adjusted financial planning, and the development of insurance products that account for long-tail events. By proactively investigating these issues and implementing mitigation strategies, the industry can enhance its resilience and ensure the long-term stability of solar investments in an increasingly uncertain world.



3 DECISION MATRIX

Every PV project can be different especially when it involves various market segments, products, etc. Stakeholders can vary from projects to projects, when they are involved and along which phases of the value chain, they are active. In general, there is no right or wrong, and similar projects can experience different workflows. However, for sake of introducing cost-effective considerations and quality gates, it is important to map the workflow in a matrix with predefined stakeholders and value chain steps. The framework highlights the interconnected nature of decisions and their long-term impact on asset value, making it an essential tool for strategic asset management and performance optimization.

In general terms the essential stakeholders involved in a PV project can be identified as:

- Investors: Private Equity / Bank
- Asset Owners / Asset Managers
- Project developers
- EPCs
- O&M operators
- Insurance companies
- Product Manufacturers
- Service providers
- Consultants
- Authority / Incentives / Regulatory stakeholders

while the phases of the value chain of a project can be broadly described as:

- project development;
- engineering;
- procurement;
- construction;
- operation;
- decommissioning / end of life.

It is difficult to generalize the workflow; at the same time, it is a very important exercise as it allows us to clearly highlight the following elements among many others:

- Stakeholders that are active in a part of the value chain that do not naturally belong to them: this can create issues related to quality, lack of focus by the stakeholder, etc.
- Different stakeholders can be vertically integrated within the same company.
- In some market segments, specialized stakeholders might be missing thus opening opportunities to new businesses.
- Define key parts of the workflow where quality gates must be introduced.



3.1 Value Chain of PV Projects

As a tool to achieve the objectives described above, a decision matrix has been introduced. The decision matrix is built with the rows representing the various stakeholders involved in the process, the columns the phase of the value chain of an PV project.

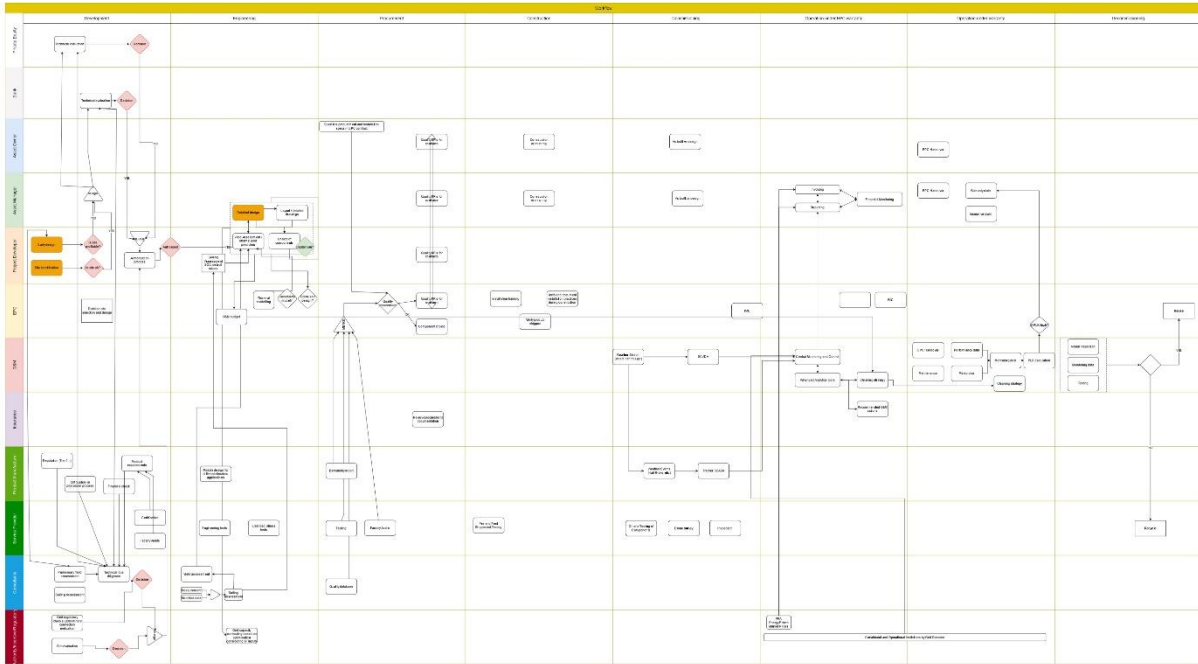


Figure 5: General view of the decision matrix.

During the project all the partners were involved together with external stakeholders in supporting the exercise of completing the mapping. In the following section we will provide some examples where the workflow mapping is already in an advanced stage with the aim of providing a clearer explanation about the process.

To have an easier representation of the decision matrix, a stakeholder focused view was introduced. This representation was also used for the feedback phase as it immediately shows the knowledge gap in the workflow and the nearest interaction between stakeholders. The following figures show the current situation of the decision matrix description for all stakeholders. The workflow related to the specific stakeholders is in bold and the workflow includes the “nearest neighbour” interaction, i.e. the first level interaction with other stakeholders. For Figure 11 and Figure 13 we have not provided a detailed explanation as details are lacking.

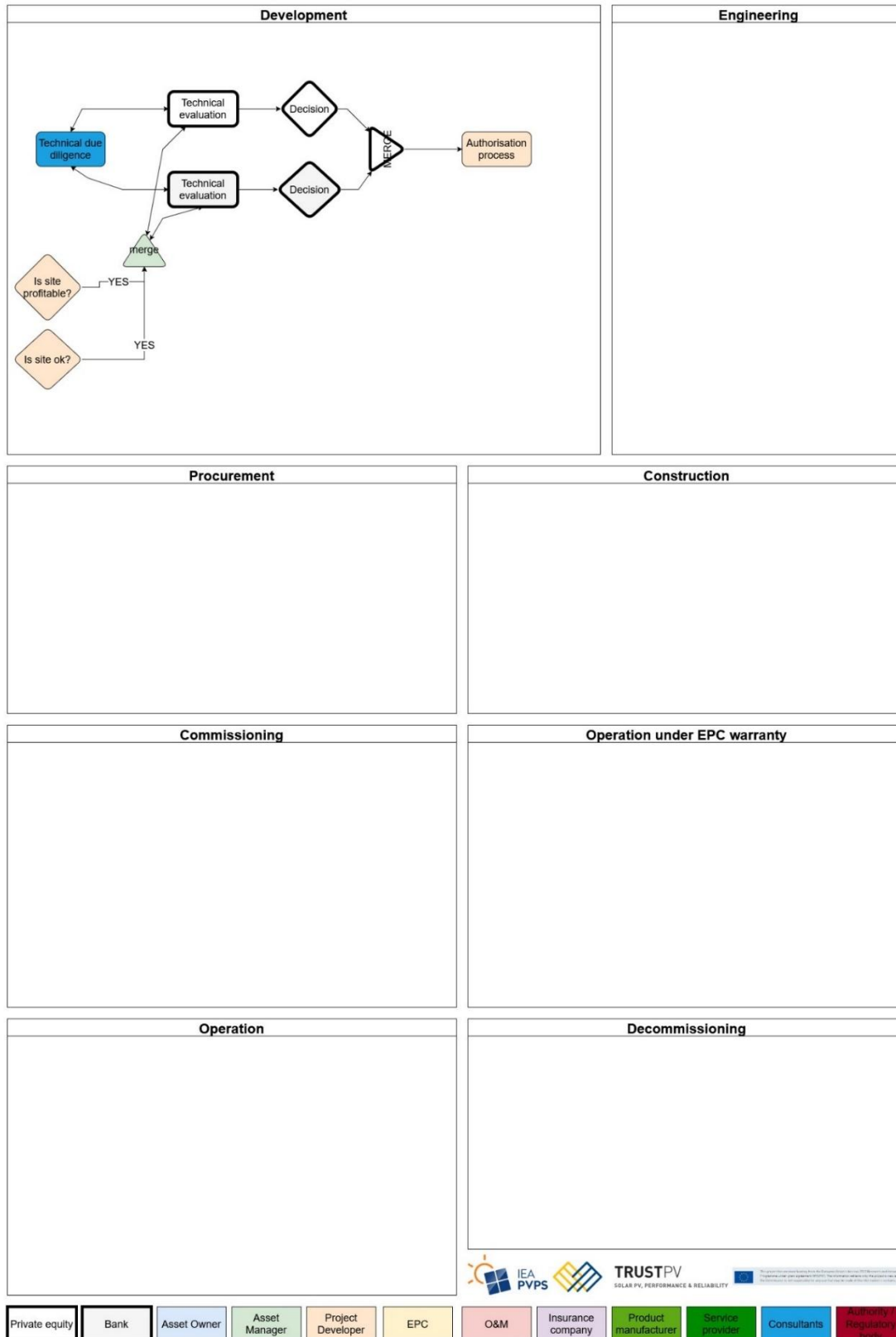


Figure 6: Decision workflow for stakeholders "Banks/Investors".



3.1.1 Banks / Private equity / Investors

In the development phase, investors are primarily involved in:

- Overseeing the "Technical due diligence" process (usually provided by consultants)
- Following the decision-making path through multiple "Technical evaluation" stages
- Having significant interest in the "Is site profitable?" decision gate, which is a critical checkpoint for financing decisions
- Having oversight of the "Is site, ok?" verification
- Being involved in the "Authorization process" (in the hands of Project Developers)

The key focus for investors in this workflow is concentrated in the Development phase, where the financial viability and risk assessment of the project are determined. The process shows a structured approach to project evaluation where:

1. Technical due diligence provides the foundation for risk assessment
2. Multiple technical evaluations ensure thorough project vetting
3. Profitability assessment serves as a key decision point
4. Site suitability verification adds another layer of risk mitigation
5. Final authorization process completes the initial project validation

This workflow reflects the investors' primary concerns:

- Risk assessment and mitigation
- Project viability verification
- Technical and financial due diligence
- Authorization and compliance verification

Notably, while investors are key stakeholders in project financing, their direct workflow involvement is front-loaded in the development phase, where the project's fundamental viability is established. This makes sense as this is the critical period for determining whether to proceed with project financing.

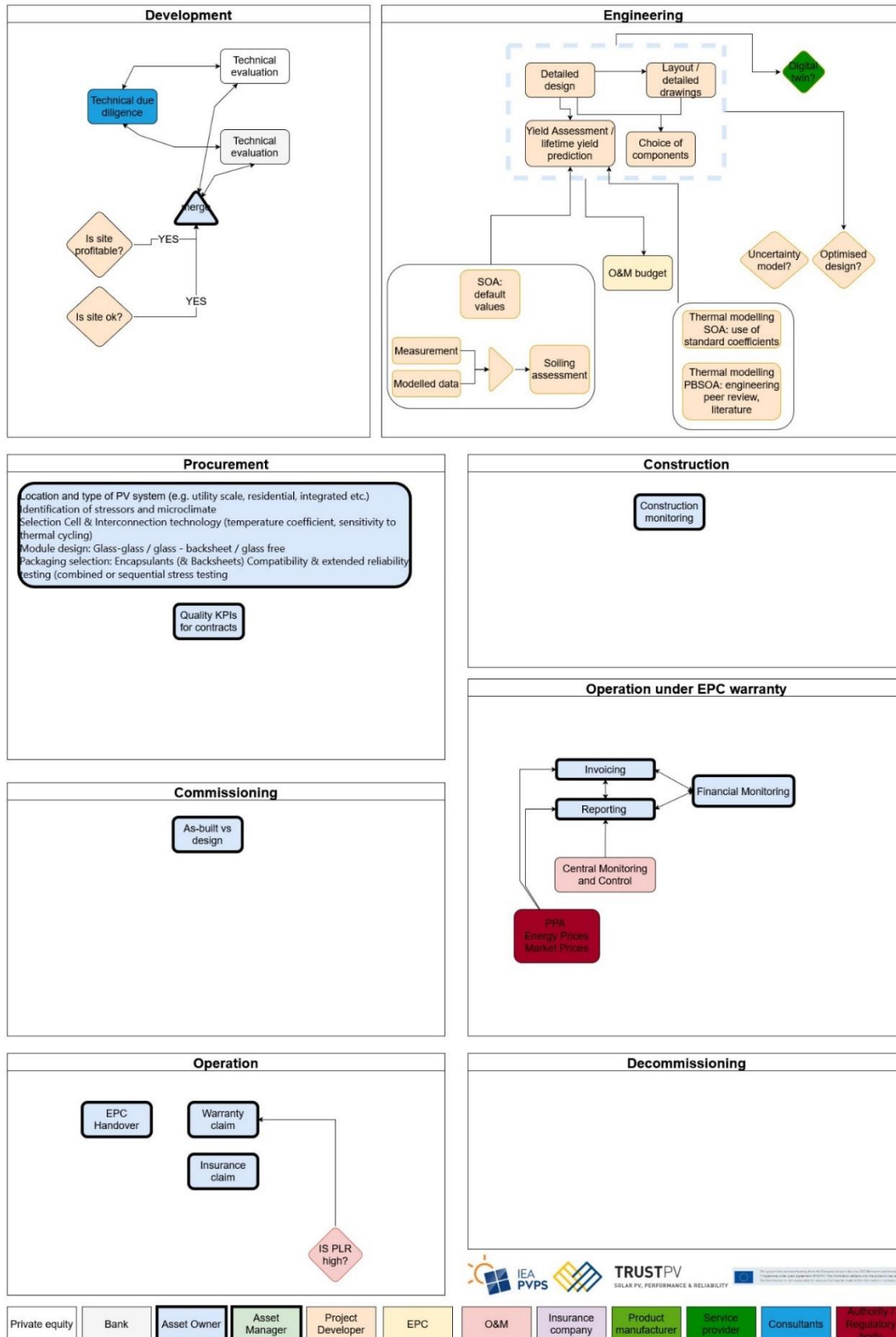


Figure 7: Decision workflow for stakeholder "Asset Owner/Asset Manager".



3.1.2 Asset Owners/Managers

From the diagram, the Asset Owner/Manager's specific workflow (shown in bold black borders) focuses on several key activities:

In the Operation phase, Asset Owners have direct responsibility for:

- "EPC Handover" - receiving the asset from the EPC contractor
- "Warranty claim" management
- "Insurance claim" processing

The workflow indicates that Asset Owners/Managers have a focused role in:

- Component selection decisions that impact long-term asset performance
- Budget oversight for operations and maintenance
- Managing the transition from construction to operation
- Handling performance-related claims
- Monitoring system performance through PR (Performance Ratio) metrics

Asset Owners/Managers have specific, defined responsibilities rather than involvement in all aspects of the project lifecycle. Their role is particularly concentrated in the operational phase of the project, where asset value and performance are most critical.

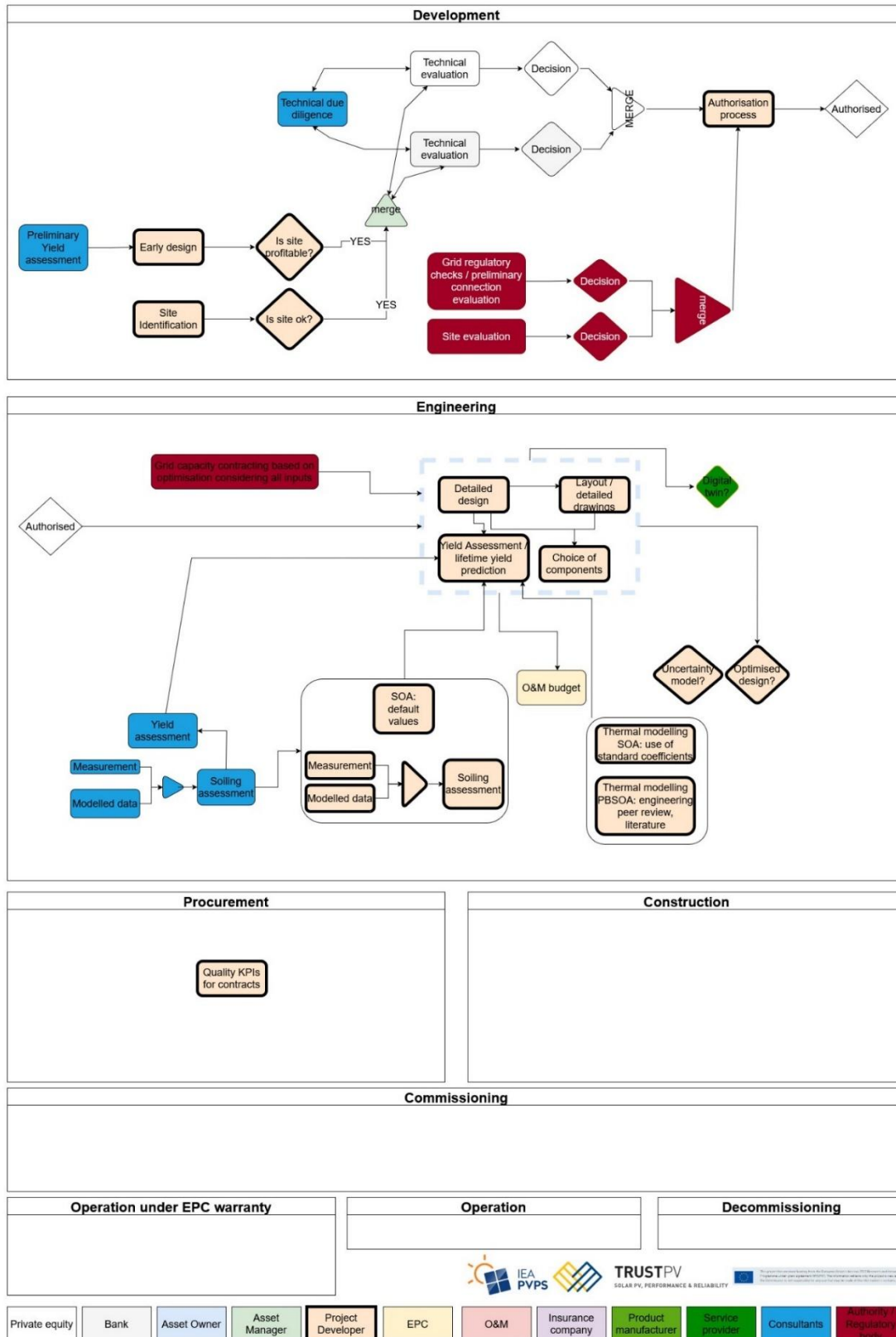


Figure 8: Decision workflow for stakeholder "Project Developer".



3.1.3 Project Developers

In the development phase, Project Developers are primarily responsible for:

1. Grid-related activities:
 - "Grid regulatory checks"
 - "Preliminary connection evaluation"
 - Associated decision points following these evaluations
2. "Site evaluation" processes and their subsequent decision points

In the Engineering phase, Project Developers are involved in:

- "Grid capacity contracting based on curtailment considering all times"
- This forms a crucial early stage of the engineering process that feeds into subsequent design work

The Project Developer's workflow shows a clear focus on:

1. Grid Integration:
 - Regulatory compliance
 - Connection feasibility
 - Capacity contracting
 - Curtailment considerations
2. Site Development:
 - Comprehensive site evaluation
 - Decision-making authority on site-related matters
 - Integration with grid connection planning

This workflow reflects the Project Developer's critical role in:

- Ensuring project viability from a grid connection perspective
- Managing regulatory compliance
- Coordinating between site constraints and grid requirements
- Making key decisions that impact the project's technical and commercial feasibility

Notably, their involvement is concentrated in the early stages of the project, particularly in Development and early Engineering phases, where fundamental project parameters are established. This makes sense as these stages set the foundation for successful project execution.

After the engineering phase, while Project Developers likely maintain oversight, they don't have specific operational tasks shown in the subsequent phases (Procurement, Construction, etc.), as their primary value-add is in the project's development stages.

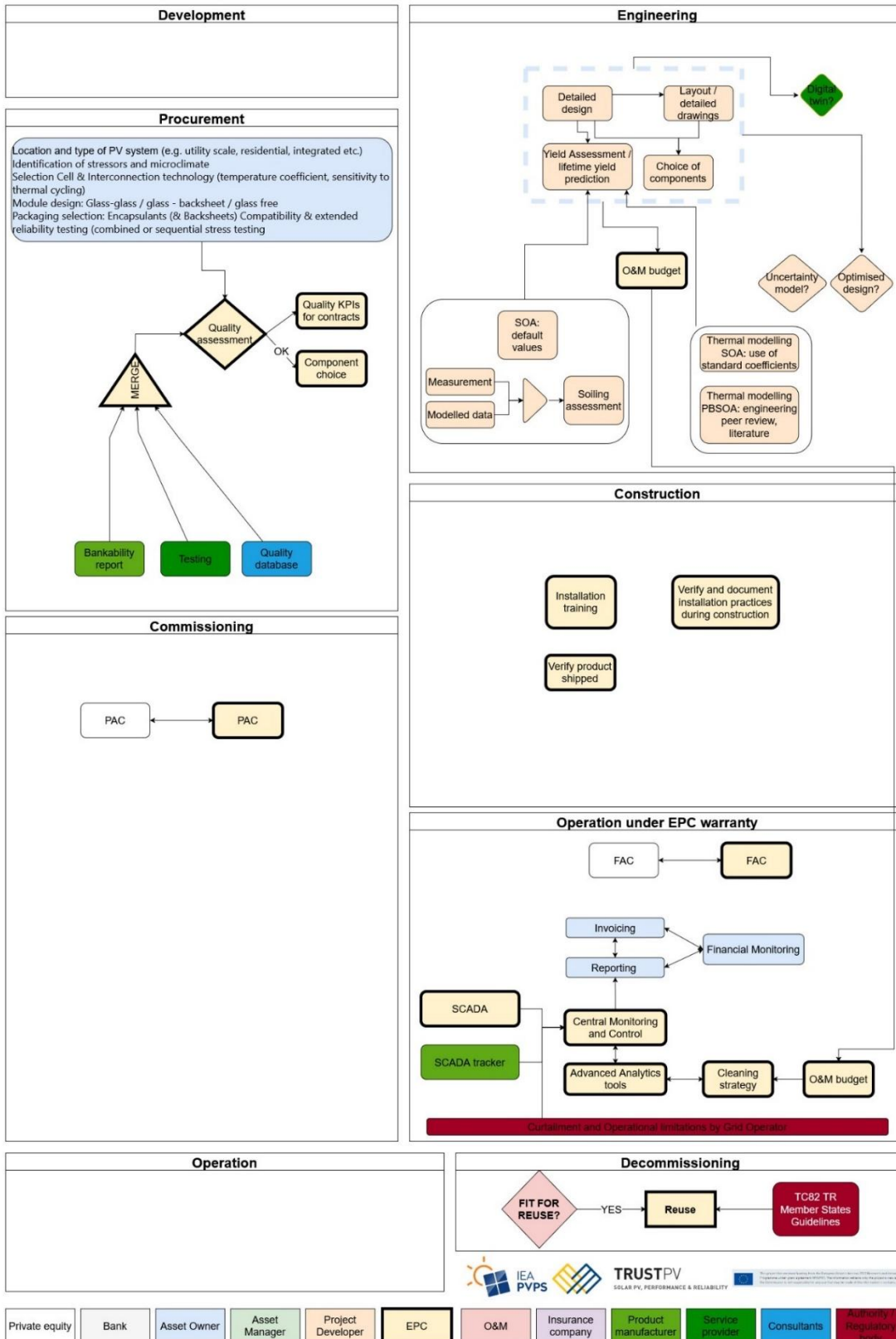


Figure 9: Decision workflow for stakeholder "EPC".



3.1.4 EPCs

In the Engineering phase:

- "Detailed design"
- "Layout/detailed drawings"
- "Choice of components"
- Involvement in "Yield Assessment/lifetime yield prediction"
- "Soiling assessment" integration

In the Procurement phase, EPCs manage:

1. Component selection process including:
 - System type and location specifications
 - Stressor and microclimate identification
 - Cell and interconnection technology selection
 - PV Module selection decisions
 - Packaging selection and reliability testing
2. Quality assurance through:
 - "Quality KPIs for contracts"
 - "Quality assessment" checkpoints
 - "Component choice" decisions

In the Construction phase, EPCs are responsible for:

- "Installation training"
- "Verify product shipped"
- "Verify and document installation practices during construction"

During Operation under EPC warranty period:

1. Monitoring and Control:
 - "SCADA" implementation
 - "Central Monitoring and Control"
 - "Advanced Analytics tools"
2. Performance Management:
 - "FAC" (Final Acceptance Certificate) processes
 - "Cleaning strategy" development
 - "O&M budget" oversight
3. Financial aspects:
 - Invoicing
 - Reporting



- Financial Monitoring

The EPC workflow demonstrates:

- Comprehensive involvement across multiple project phases
- Strong focus on technical quality and performance verification
- Integration of monitoring and control systems
- Clear responsibility for system performance during warranty period
- Handover processes and documentation requirements

This reflects the EPC's role as the primary technical implementer and system integrator, with responsibilities spanning from detailed design through construction and into the warranty period operation.

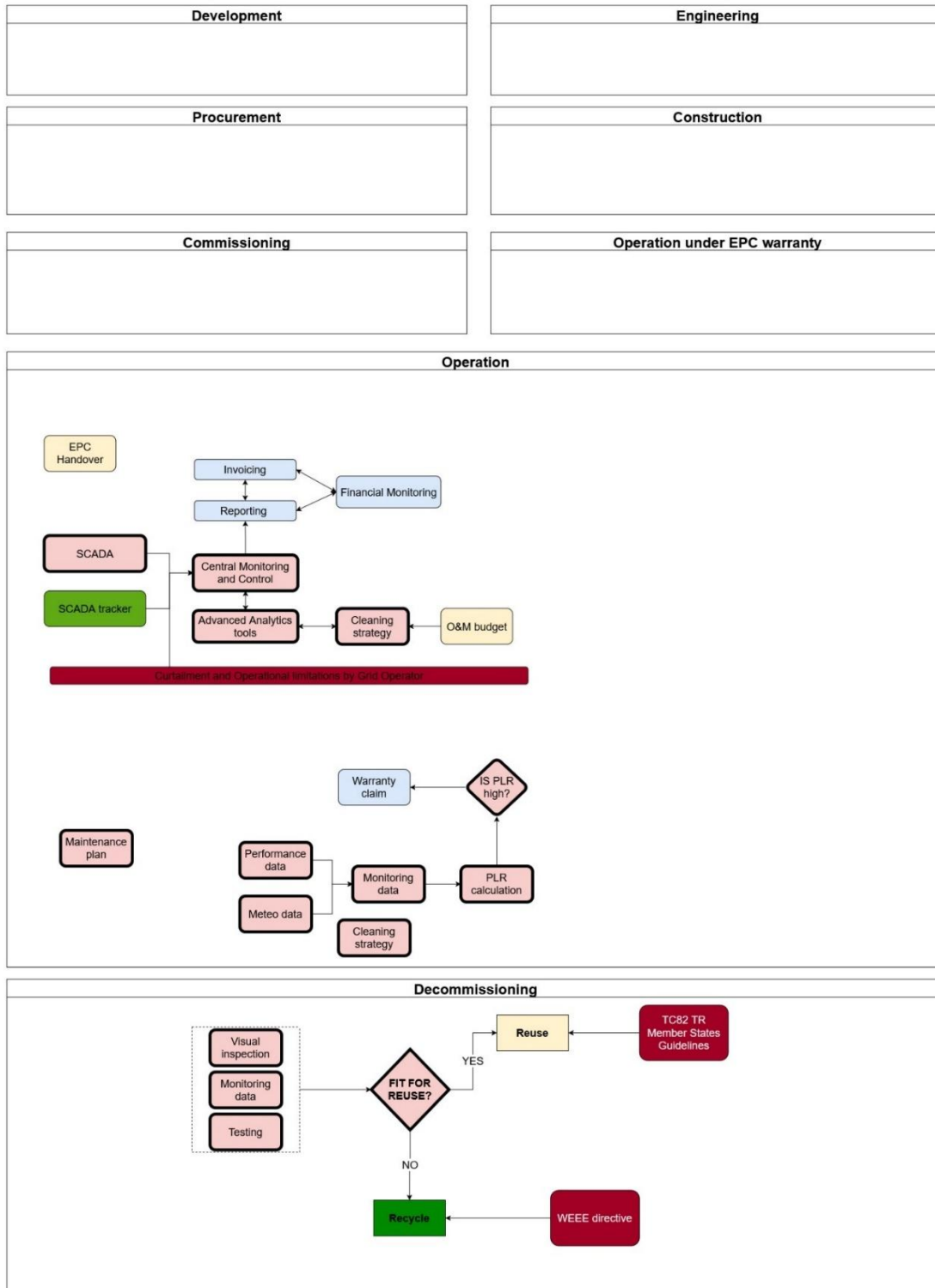


Figure 10: Decision workflow for stakeholder “Operation & Maintenance”.



3.1.5 Operation & Maintenance

In the operational phase, stakeholder O&M is heavily involved in:

1. Monitoring Systems:
 - SCADA implementation and management
 - Central Monitoring and Control
 - Advanced Analytics tools
 - SCADA from tracking systems oversight
2. Performance Management:
 - "Performance data" collection
 - "Monitoring data" aggregation
 - "PR calculation" (Performance Ratio)
 - "Meteo data" collection and analysis
 - "Cleaning strategy" development and implementation
3. Maintenance Activities:
 - "Maintenance plan" development and execution
 - Implementation of cleaning strategies
 - Management of O&M budget
4. Financial Aspects:
 - Reporting
 - Invoicing
 - Financial Monitoring

In the Decommissioning phase, O&M is responsible for:

1. End-of-Life Assessment:
 - "Visual Inspection"
 - "Monitoring data" analysis
 - "Testing" procedures
2. Reuse Evaluation:
 - "FIT FOR REUSE?" decision making
 - Following TCR2 TR Member States Guidelines for reuse
 - Compliance with WEEE directive for recycling when reuse is not viable

Key aspects of O&M's role:

- Continuous monitoring and performance optimization
- Maintenance planning and execution
- Data-driven decision making



- End-of-life asset management
- Regulatory compliance in decommissioning
- Integration of performance, maintenance, and financial aspects

This workflow demonstrates the crucial role of stakeholder O&M in maintaining operational excellence throughout the asset's lifecycle and ensuring proper end-of-life management.

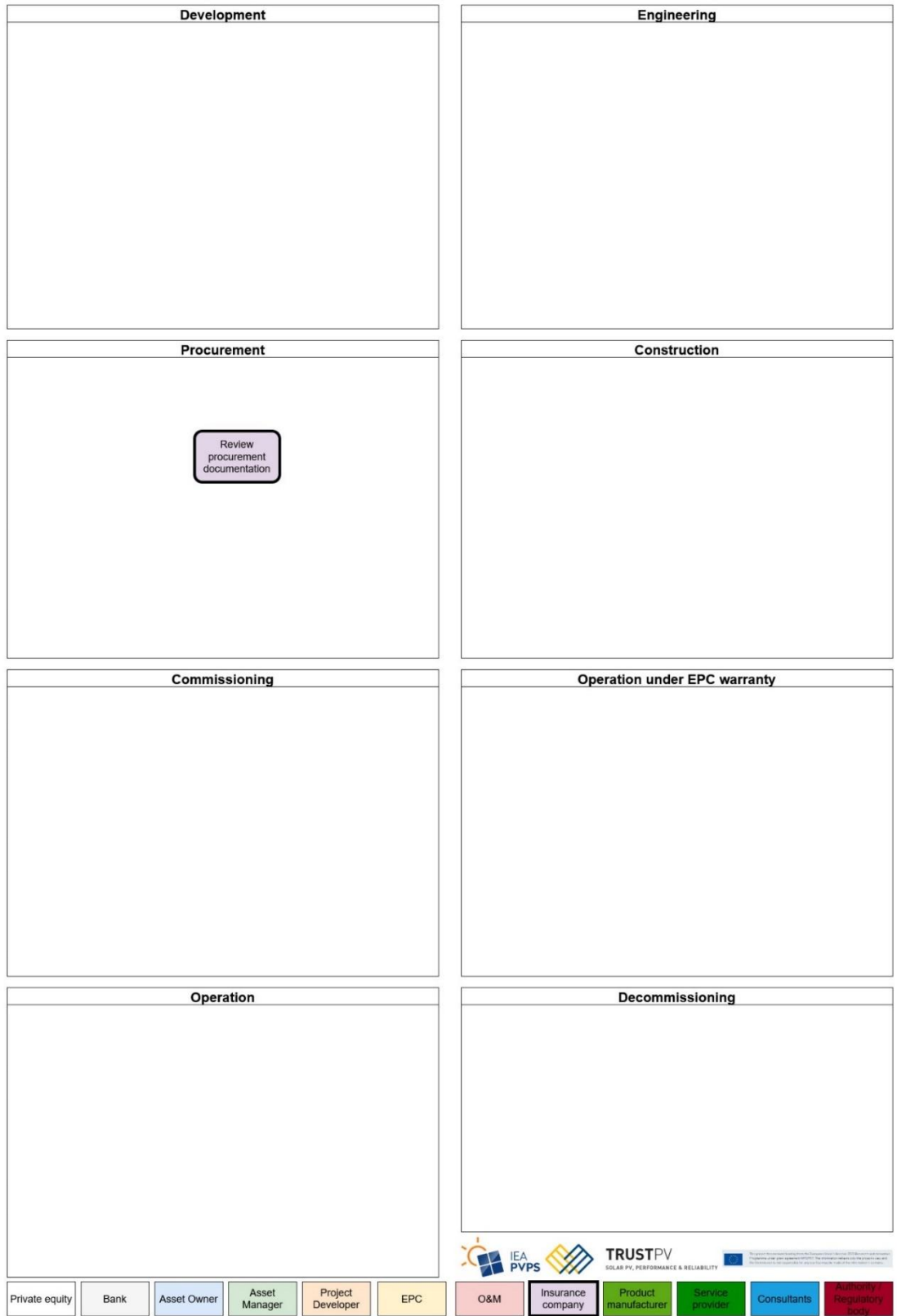


Figure 11: Decision workflow for the stakeholder "Insurance Company".

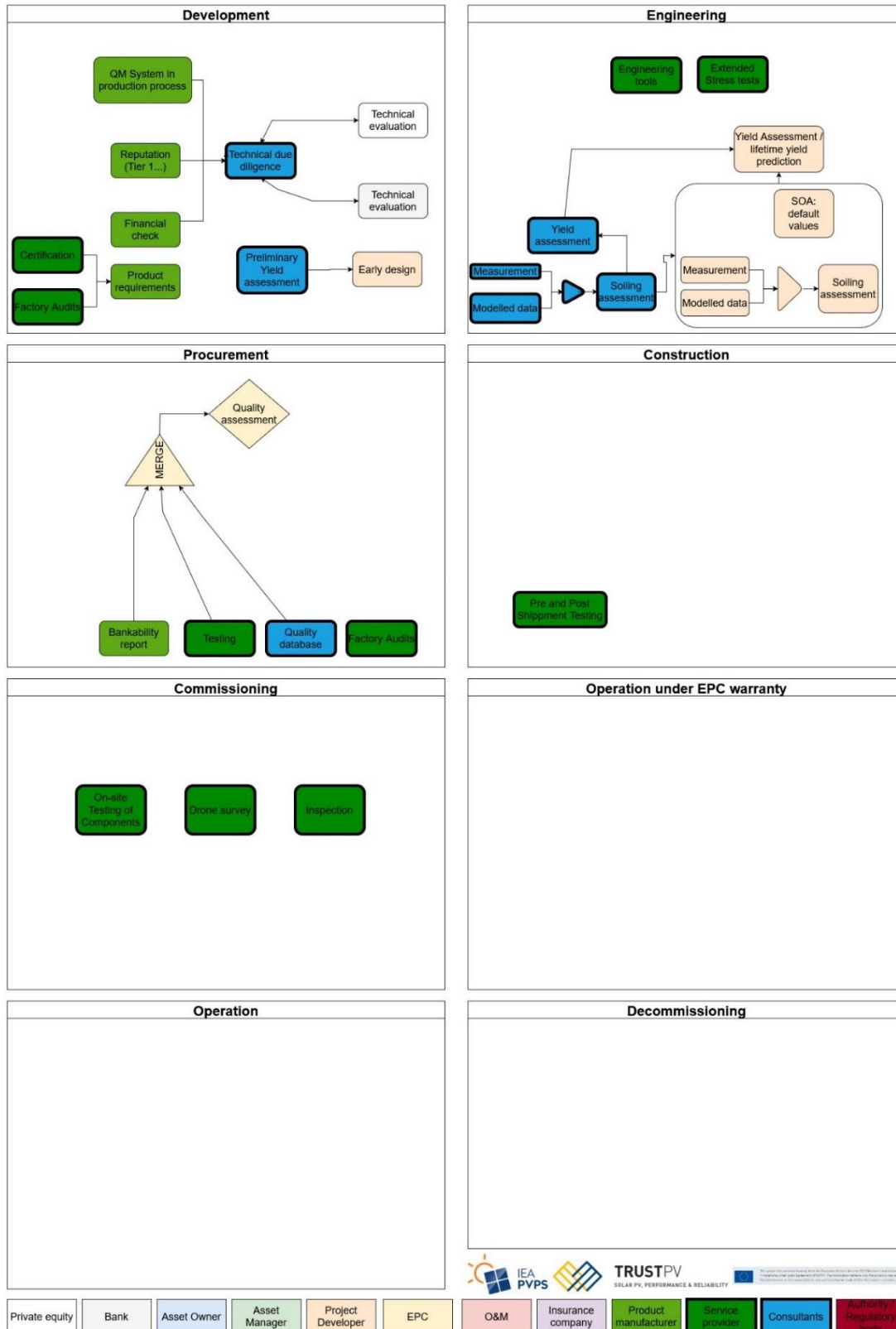


Figure 12: Decision workflow for the stakeholder "Service Provider / Consultants".



3.1.6 Service Providers / Consultants

In the Development phase, Service Provider / Consultants provide:

1. Technical Services:
 - "Factory Audits"
 - "Certification" support
2. Assessment Services:
 - "Quality management System in production process" evaluation
 - "Reputation (Tier 1)" assessment
 - "Financial check"
 - "Product requirements" verification

In the Engineering phase, they provide:

- "Engineering tools"
- "Extended Stress tests"

In the Procurement phase, they conduct:

1. Quality Assurance:
 - "Bankability report" preparation
 - "Testing" oversight
 - "Factory Audits"

In the Construction phase:

- "Pre- and Post-Shipment Testing"

In the Commissioning phase:

- "On-site Testing of Components"
- "Drone survey"
- "Inspection"

Key characteristics of the Service Provider/Consultant's role:

- Independent third-party verification and validation
- Technical expertise across multiple project phases
- Quality assurance and testing services
- Due diligence support
- Technical advisory services

This workflow highlights the Service Provider / Consultant's role as an independent expert providing technical assurance and verification services throughout the project lifecycle, from initial development through commissioning.

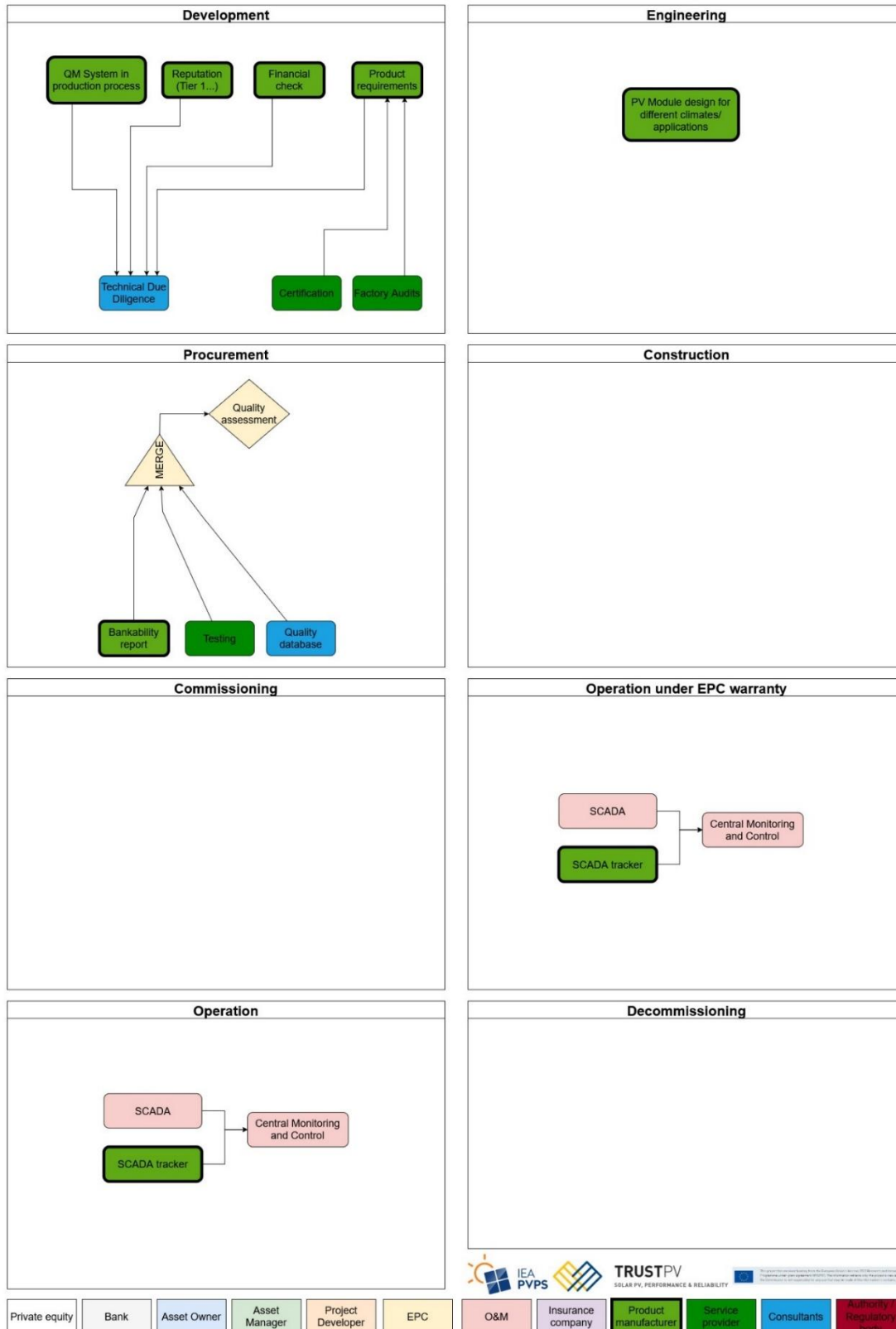


Figure 13: Decision workflow for stakeholder “Product Manufacturer”.

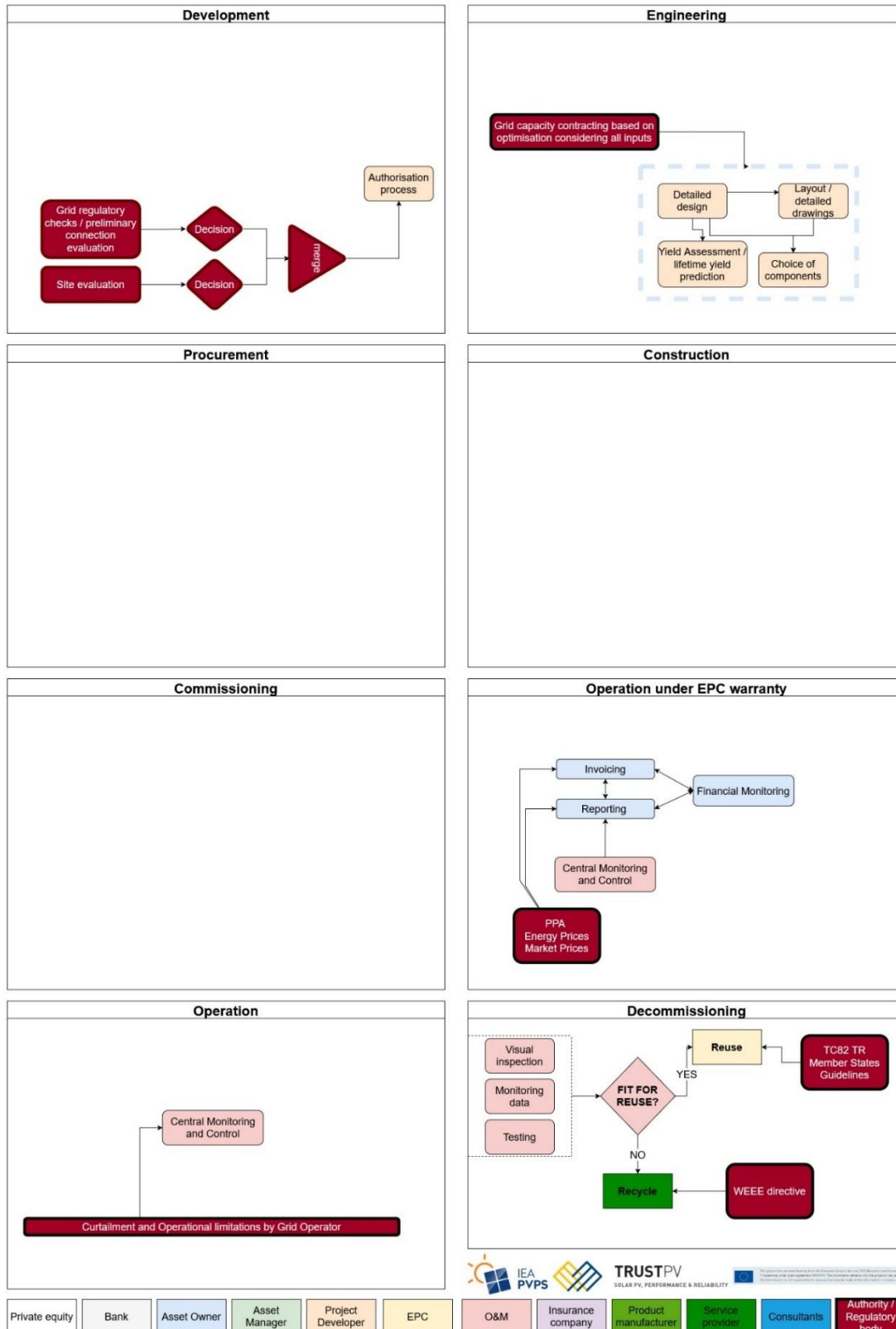


Figure 14: Decision workflow for stakeholder “Authority/Regulatory Body”.



3.1.7 Authority/Regulatory Body

In the Development phase:

1. Grid-related Oversight:
 - "Grid regulatory checks"
 - "Preliminary connection evaluation"
2. Project Approval:
 - "Site evaluation" review
 - Key "Decision" points
 - Final approval through "Authorization process"

In the Engineering phase:

- Oversight of "Grid capacity contracting based on optimization considering all inputs"

In the Operational phase:

- Setting and monitoring "Curtailment and Operational limitations by Grid Operator"
- Oversight of electricity market rules and price formation mechanisms

In the Decommissioning phase:

1. Regulatory Framework:
 - "TC82 TR and/or Member States Guidelines" enforcement
 - "WEEE directive" compliance oversight

Key aspects of the Authority/Regulatory Body's role:

- Grid connection and operation regulation
- Regulation of market structure and tariff frameworks
- Environmental compliance enforcement
- End-of-life guidelines and requirements
- Overall regulatory framework maintenance

This workflow demonstrates the Authority/Regulatory Body's crucial role in:

- Ensuring compliance with grid regulations
- Maintaining market structure
- Setting operational limitations
- Enforcing environmental standards
- Providing regulatory framework for decommissioning

Their involvement spans the entire project lifecycle, with particular emphasis on initial approval, operational constraints, and end-of-life requirements.



3.2 Quality Gates

The process of quality assurance is of fundamental importance to ensure that all elements of a project are of high quality for all involved stakeholders. In the project “Solar Bankability”, the Bankability of a project – strictly connected with quality – was described as “active quality management process, where all stakeholders in the approval process of a PV project attempt to identify legal, technical, and economic risks throughout the entire project life cycle. These risks need to be quantitatively and qualitatively assessed, managed, and controlled. Once the risks are defined, their impact can be vastly reduced by preventive mitigation measures, corrective mitigation measured, and transfer of risks to other stakeholders (for e.g. insurance companies). The remaining risks will stay with the owner or operator of the asset. Mapping the workflow allows for an effective visualisation of the process where “quality gates” can be introduced.

A “Quality gate” is a concept widely applied in the IT sector and refers to a milestone in a project that requires that predefined criteria can be met before the project can proceed to the next phase. It is important that quality gates are included after a clear cost-benefit analysis and the expectation is that more quality gates are introduced in the initial phase to prevent the manifestation of risks, rather than in later stages where the correction of failures and low quality can become very expensive and not feasible. Early quality gates tend to shift costs from corrective OPEX to preventive CAPEX, with net positive impact on the LCOE.

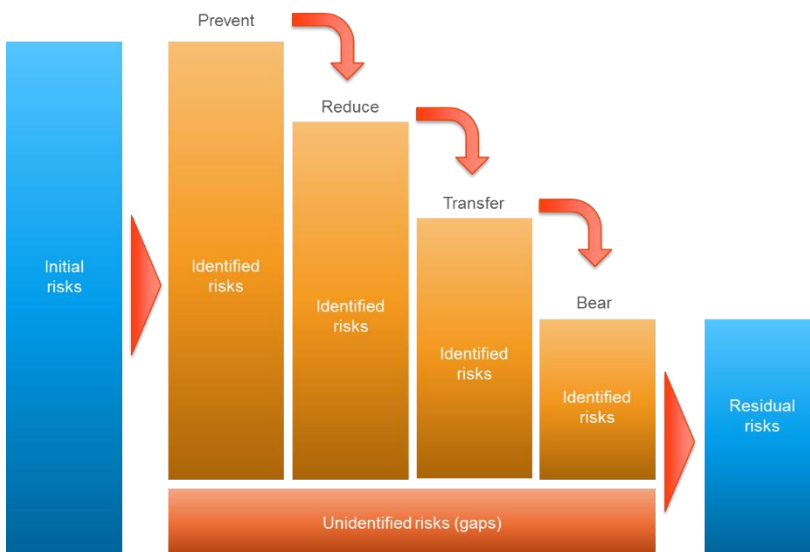


Figure 15: Technical risk management (Source: H2020 project Solar Bankability).

Development Phase: The development quality gates form a structured validation pathway starting with technical due diligence that incorporates preliminary yield assessment data. This feeds into parallel technical evaluation streams that merge for consolidated decision-making. Site validation proceeds through two crucial checkpoints: site profitability and general site suitability assessments. Grid regulatory compliance and connection evaluation form another critical gate, culminating in the final authorization process.

Engineering Phase: Engineering quality gates begin with grid capacity contracting optimization that accounts for all potential curtailment scenarios. The design validation pathway flows from detailed design through layout and detailed drawings to reach design optimization. Yield assessment forms a comprehensive gate incorporating for e.g. soiling assessment that combines measured and modelled data, validates SOA default values, and confirms lifetime yield



prediction accuracy. Detailed modelling verification is another example of quality gates (see for example, thermal modelling).

Procurement Phase: Procurement quality gates centre on component reliability and performance validation. The component selection criteria gate verifies PV system type specifications, stress testing for thermal cycling and microclimate conditions, and module design configurations including glass-glass and backsheet options. The quality assessment gate merges inputs from bankability reports, testing results, quality database verification, and factory audit outcomes to ensure comprehensive quality control.

Construction Phase: Construction quality gates ensure installation integrity through a sequence of verifications. These begin with pre-shipment product verification, proceed through installation training completion, and continue with ongoing construction practice documentation. The phase concludes with thorough post-installation verification.

Commissioning Phase: Commissioning quality gates establish operational readiness through the PAC process completion. This includes verification of SCADA system implementation, comprehensive on-site testing of components, and thorough inspection, including drone survey verification.

Operation under EPC Warranty: Initial operation quality gates focus on performance monitoring systems. These include SCADA implementation and tracker verification, central monitoring and control system validation, and advanced analytics tools implementation. The gates extend to cleaning strategy effectiveness and O&M budget adherence verification.

Operational Phase: Ongoing operation quality gates track performance through PR and PLR calculation, integrating performance data, monitoring data, and meteorological data along with cleaning strategy effectiveness. Financial monitoring gates verify proper invoicing and reporting systems. Warranty claim verification based on PLR thresholds ensures performance accountability.

Decommissioning Phase: End-of-life quality gates ensure proper asset disposition through a comprehensive reuse assessment protocol. This includes visual inspection, monitoring data analysis, and testing verification. Compliance verification ensures adherence to TC82 TR and/or Member States Guidelines for reuse and WEEE directive for recycling, leading to a final disposal decision between reuse and recycling pathways.

3.3 PV Applications

The rapid growth in PV deployment is leading to an increasing diversity of PV applications. On one hand, the combination of bifacial modules and trackers has proved to significantly reduce the levelized cost of electricity in most locations [45]. On the other hand, the increasing land requirement associated with the large-scale deployment of PV has led to the development of innovative solutions, such as floating photovoltaics and agrivoltaics.

These various applications however demand tailored decision-making approaches, as each of them presents unique challenges and opportunities and can be influenced by site- and application-specific factors such as terrain morphology, water body characteristics, and agricultural activities. In addition, the decision process has also to consider that different stakeholders can be involved, each bringing their own interests and concerns. This means that the decision flow should be adapted to the specific requirements of each application. In this section, key considerations for three specific PV applications are discussed.



3.3.1 PV Bifacial Tracking Systems

Bifacial PV tracking systems share the same risks as any ground-mounted PV system, but they also introduce specific risks associated with bifacial PV modules and tracking technology. These risks are discussed in detail in the report “Best Practices for the Optimization of Bifacial Photovoltaic Tracking Systems” [46] (IEA-PVPS T13-26:2024). While trackers can enhance energy yields over the lifespan of a PV plant, they also add complexity by introducing mechanical systems that may lead to additional failure modes and increased operation and maintenance (O&M) costs.

The design of trackers varies significantly among manufacturers, and selection should be tailored to site conditions. For instance, sites with complex topography may benefit from trackers that allow for independent movement of each row, while locations with extreme temperatures might prefer trackers that do not rely on batteries. During the engineering and design phase, it is crucial to minimize obstructions on the rear side of the modules to ensure sufficient light reaches the back of the array. Accurate time-dependent assessment of ground albedo, including predictions regarding the duration of snow cover or seasonal vegetation patterns, is essential for yield assessment. Notably, predicted performance results from yield assessment software for bifacial PV tracked systems exhibit greater variability compared to monofacial and fixed-tilt systems. Therefore, developers are advised to utilize a range of models to better evaluate energy yield uncertainty.

The monitoring system for the plant should adhere to bifacial recommendations outlined in IEC 61724-1, which specify the number and type of irradiance sensors, albedometers and other monitoring devices. Specific guidance on the positioning of front and rear plane of array (POA) pyranometers and back-of-module temperature sensors can be found in [46], IEA-PVPS T13-26:2024. Inclinometers to measure tracking angles can be quite helpful for monitoring the condition state of the trackers during the operation phase.

Advanced tracking algorithms can protect modules from damage caused by hail and high wind events; however, these features are not yet standardized, resulting in varying capabilities and features across different tracker products. All these solutions depend on accurate extreme weather forecasts or onsite sensors.

3.3.2 PV Floating Systems

Floating Photovoltaic (FPV) technology represents an emerging frontier in renewable energy that, while sharing fundamental characteristics with traditional ground-mounted photovoltaic systems, introduces significant challenges and considerations unique to aquatic environments. The development of FPV follows a similar procedural framework to conventional utility-scale PV but differs substantially in technical implementation, operational requirements, and environmental considerations.

The planning and design phase for FPV projects typically spans 3-5 years, notably longer than ground-mounted equivalents, due to additional complexities in site selection and regulatory compliance [47]. These projects demand specialized environmental assessments that account for water dynamics, bathymetry surveys, and soil analyses essential for mooring systems. Unlike ground-mounted systems, FPV installations must consider water-specific factors such as wave action, water level fluctuations, and potential impacts on aquatic ecosystems.

Technical design for FPV introduces elements entirely absent from traditional PV installations. The selection of appropriate floating structures (floaters) requires careful consideration of



buoyancy, stability, and resistance to biofouling in water environments. The mooring and anchoring systems represent critical components unique to FPV that must secure the installation against environmental forces while allowing for some degree of movement. These systems must be engineered to withstand both hydrodynamic and aerodynamic loads, requiring sophisticated modelling approaches not necessary for ground-mounted equivalents.

The installation process for FPV presents distinct logistical challenges, typically involving shore assembly followed by water deployment. This necessitates specialized equipment for water-based transport and installation, properly sloped launching ramps, and temporary mooring systems during deployment—factors irrelevant to land-based installations. The assembly zones, storage areas, and access points must all be designed with water-based operations in mind.

Operation and maintenance of FPV systems inherently involves greater complexity and cost compared to ground-mounted equivalents. Access to modules for inspection and repair requires specialized approaches and safety protocols for working over water. Maintenance activities must account for unique degradation mechanisms such as humidity exposure, dynamic loading from wave action, and biological fouling. The OPEX for FPV installations is consistently higher than traditional ground-mounted systems, with significant variability depending on the specific water environment (small inland lakes versus offshore installations).

Reliability challenges [48] for FPV include both standard PV concerns and water-specific issues. While conventional components like modules and electrical systems face similar failure modes to ground installations, they encounter additional stresses from water exposure and potential dynamic loading. Components unique to FPV, such as floaters and mooring systems, introduce entirely new failure modes including fatigue from wave action, biofouling, and connector failures between floating elements.

The regulatory landscape for FPV adds layers of complexity not encountered in ground-mounted installations. Projects must navigate water rights, potential impacts on navigation, specific environmental permits for aquatic ecosystems, and often specialized decommissioning requirements for water body restoration.

As an emerging technology, FPV lacks the established standards and norms that guide traditional utility-scale PV development. This creates both challenges and opportunities, as best practices continue to evolve through knowledge sharing among industry participants. Proper tracking of maintenance activities and systematic analysis of failure modes will be essential to improving reliability and reducing costs as the sector matures. The advancement of FPV technology represents an important expansion of solar energy's potential, allowing renewable power generation on water bodies while preserving valuable land resources.

3.3.3 APV Systems

Agrivoltaic systems carry similar risks to traditional ground-mounted PV systems. However, the integration of agricultural elements introduces additional ones. These risks are comprehensively summarized and discussed in the Task 13 Report “Optimization of Photovoltaic Systems for Different Applications” (IEA-PVPS T13-39:2026) [49]. They include hazards associated with the operation of agricultural machinery, the presence of livestock, and the application of pesticides and fertilizers, all of which can increase the likelihood of damage to PV modules, supporting structures, and cabling. While beneficial for solar energy conversion, crops and related practices such as evapotranspiration and irrigation may expose PV modules to higher humidity levels, thereby increasing the risk of moisture ingress [50].



The design of agrivoltaic systems is influenced by various factors, including the system configuration (such as interspace, overhead, fixed or dynamic systems with trackers), agricultural practices (like grassland farming, arable farming, or horticulture), the specific crops being cultivated, and the agricultural machinery that will be used throughout the system's lifespan. Once the configuration is established, the density and technology of the photovoltaic (PV) modules are designed to achieve specific irradiation levels or crop yield to comply with regulatory frameworks. Recent trends indicate that the definitions of agrivoltaic systems in legislation often include specific crop-related key performance indicators. This design process is thus further complicated by the need for integrated modelling platforms that can simulate the impacts of shading on microclimates and crops, allowing for an assessment of crop performance prior to installation. However, very few integrated modelling platforms are currently available, despite existing regulations. Additionally, the same crop can produce different results in the same system configuration from year to year due to varying weather conditions. Therefore, multi-year and multi-crop simulations should be conducted to identify the optimal system design.

The configuration of the agrivoltaic system and the microclimate created by the PV modules not only influence crop growth but can also enhance PV electricity production through increased wind speeds, higher heat loss coefficients, and lower operating temperatures. However, agricultural activities can negatively impact PV yield, primarily due to soiling issues. Consequently, accurate assessments of PV yield and strategies to mitigate adverse effects should be incorporated during the design phase. Another critical factor affecting PV yield is the albedo value, which can fluctuate significantly from season to season and year to year. This variability is linked to agricultural management practices, crop phenological phases, and crop selection. Yet, these factors are rarely included in commercial software, as they are typically associated with research activities. From an energy conversion perspective, operational strategies of agrivoltaic systems equipped with trackers can be tailored not only to maximize electricity production, as in conventional PV systems, but also to optimize a balance between maximizing both crop yields and energy output. These strategies often utilize anti-tracking techniques to ensure that crops receive sufficient irradiation during critical phenological phases or specific times of the day, which can, in turn, have detrimental effects on energy production.

The monitoring system of agrivoltaic systems is built upon the frameworks used for conventional monofacial or bifacial PV systems. However, it is essential to also consider the agronomic aspects of the system, which include monitoring crop performance, soil status, and microclimate conditions. These measurements can be taken using either conventional methods or vision-sensing technologies to ensure compliance with current laws and standards that mandate the monitoring of system performance and agricultural activities. It is planned to extend the boundaries of the decision matrix to hybrid-asset activities and the new upstream decision points they introduce, e.g. dispatch strategy choices feeding EPC contracts.

3.4 Geographic Regions

Workflows as mapped in section 3.1, stakeholders' involvement and decision can also vary depending on a regional basis. For example, O&M in Australia varies strongly according to the location of the PV plant, the distance to nearby population centres, and the distance to other (PV) assets managed by the O&M provider. These factors affect how staffing and spare parts are managed: in some cases, staff and spare parts are assigned to a single (usually utility-scale) PV plant, whereas sites where multiple PV assets are within driving distance can have an O&M team and centralized spare parts available. For (very) remote PV systems where no



qualified staff is available, O&M is typically a scheduled activity, and response times are measured in days, rather than hours.

Experience from the 14 Large-Scale Solar (LSS) utility-scale PV projects supported by the Australian Renewable Energy Agency (ARENA) built in the period 2017-2019 indicates that OPEX costs varied between AU\$10k/MWp/y and AU\$40k/MWp/y, reflecting scale effects, market maturity, and relative remoteness of some PV farms [51]. Critical spare parts (e.g. complete inverters or inverter power stacks) and associated spare parts management have been identified by six out of the fourteen LSS projects as a major challenge, which are combined with long shipping times to Australia and Australia-specific standards, resulting in delays or downtimes that can last for months [52].

The rapid growth of utility-scale PV systems in Australia 2015-2025 strongly affected project economics, with much higher curtailment than anticipated, and rapid reductions of Marginal Load Factors (MLFs) [53]. MLFs are an energy scaling factor for a generator or load connected to a node on the Australian National Electricity Market (NEM), assigned yearly by the Australian Energy Market Operator (AEMO), representing the marginal change in loss between a connection point and the regional reference node (RRN). An MLF of 1.07 increases the financial pay-out to a generator at that location by 7%, and costs 7% more, incentivizing more generation or less demand at that location. If multiple generators (e.g. PV farms) connect to the same electrical node within less than a year, the MLF may change from greater than one to less than one, thereby strongly reducing the profitability of the generator.

PV system design and subsequent maintenance varies strongly within Australia [54], reflecting the large scale of the country, weather patterns, associated microclimates and flora and fauna. Given the size of the country, there is a lack of high-resolution data, e.g. site-specific soiling, which affects the yield, as well as O&M approaches that can and should be used. Cyclonic regions may require lower module tilt angles when using larger PV modules, reducing the possible yield that can be achieved, compared to using smaller module sizes [55]. Similarly, the electrical layout of the grid (meshed versus radial with long lines) can affect operational demands on PV plants, affecting not only reactive power provision capabilities, but also considering how the inverter's MPPT algorithm affects the DC bus and subsequently the power plant AC voltage and harmonic quality [56].



4 CASE STUDIES

4.1 Quality-Controlled PV Modules - Optimization by Extended Standard Testing, Post-Shipment Testing

This case study highlights the necessity of quality control procedures throughout the lifespan of PV modules, including both the manufacturing stage and installation [57]. Conventional in-line power measurements taken at the factory serve as a valuable reference point, yet they may not accurately represent the actual performance of PV modules under real environmental conditions. Failing to implement comprehensive quality control measures can result in the acceptance of suboptimal modules, leading to significant additional costs and potential performance issues in the field.

4.1.1 Current practises for quality-controlled PV modules

The primary objective of quality control for PV modules is to verify and ensure the general performance and reliability of PV modules. On-site inspection methods for PV modules and PV strings are helpful tools to identify the drivers for underperforming PV power plants. They can be applied at different phases of PV projects:

- a) **Sampling inspection of PV module shipments:** A systematic testing of PV module shipments at various stages of production, including the manufacturing site, warehouse, and PV power plant.
- b) **Acceptance testing of PV array prior to commissioning:** A comprehensive assessment of the PV array before its deployment and commissioning, to verify its performance and functionality according to predetermined specifications and standards.
- c) **Pre-transfer ownership assessment:** Evaluation and verification of a PV array's quality and performance before transferring ownership or responsibility for its maintenance and operation.
- d) **Periodical quality and maintenance (Q&M) measures:** Regular inspections and maintenance activities undertaken to ensure the continued performance and reliability of the PV array throughout its lifecycle.

4.1.2 Best practice for post-shipment testing with a mobile lab

Best practices are shown based on a case study to evaluate the effectiveness of post-shipment tests carried out with a mobile laboratory [58] (see Figure 16 and Figure 17). The mobile laboratory, built to meet IEC 61215 and IEC 60904 standards, is equipped with state-of-the-art technology, including an A+A+A+ LED sun simulator and a high-resolution electroluminescence camera. This advanced setup enables the collection of precise measurements and swift results, comparable to those obtained under laboratory conditions. Testing batches are selected based on the guidelines of ISO 2859-1, considering the potential for degradation and damage caused by transportation.

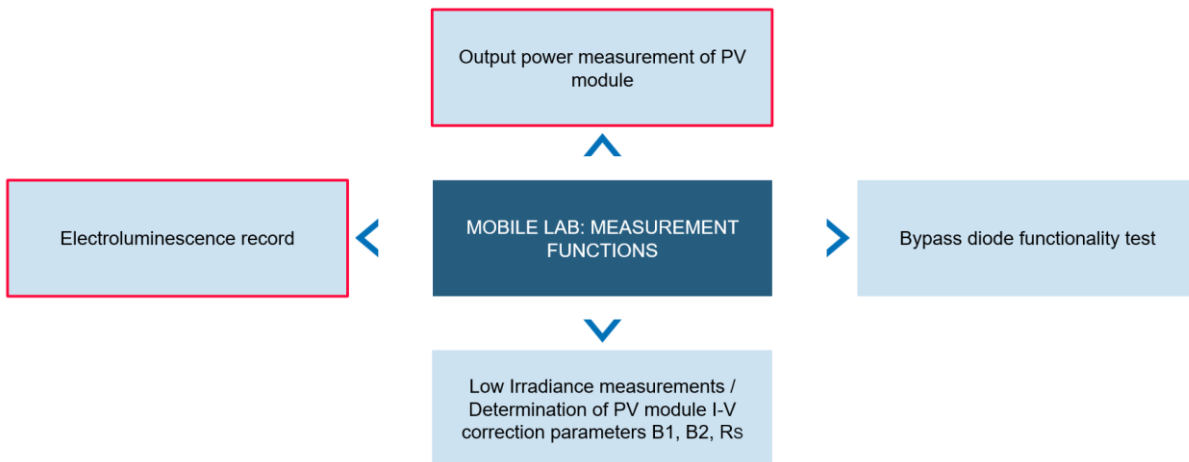


Figure 16: Measurement functions of the mobile lab.

A total of over 4000 state-of-the-art commercial PV modules from 20 different PV projects and five different manufacturers were evaluated on-site using a high-level measurement protocol, with a power measurement uncertainty of less than $\pm 2.7\%$. This process yielded a comprehensive dataset, providing valuable insights into the post-shipment performance and reliability of PV modules. These findings allow the detection of changes in quality throughout the production process and manufacturing sites, identify any transportation-induced damages, and contribute significantly to ongoing quality assurance improvement efforts within the PV industry.



Figure 17: Mobile lab on-site.

The analysis, shown in Figure 17, revealed that in-line power measurements conducted at the factory overestimated the power output by up to 4%. These deviations from nominal power ratings varied significantly among different manufacturers. Even modules of the same type exhibited differences in power output depending on the specific batch delivered. This inconsistency highlights the necessity for quality control processes to ensure the reliability and performance of photovoltaic modules. Consequently, end-users should be aware of these potential discrepancies and consider additional independent testing to verify the actual performance of the PV modules received.

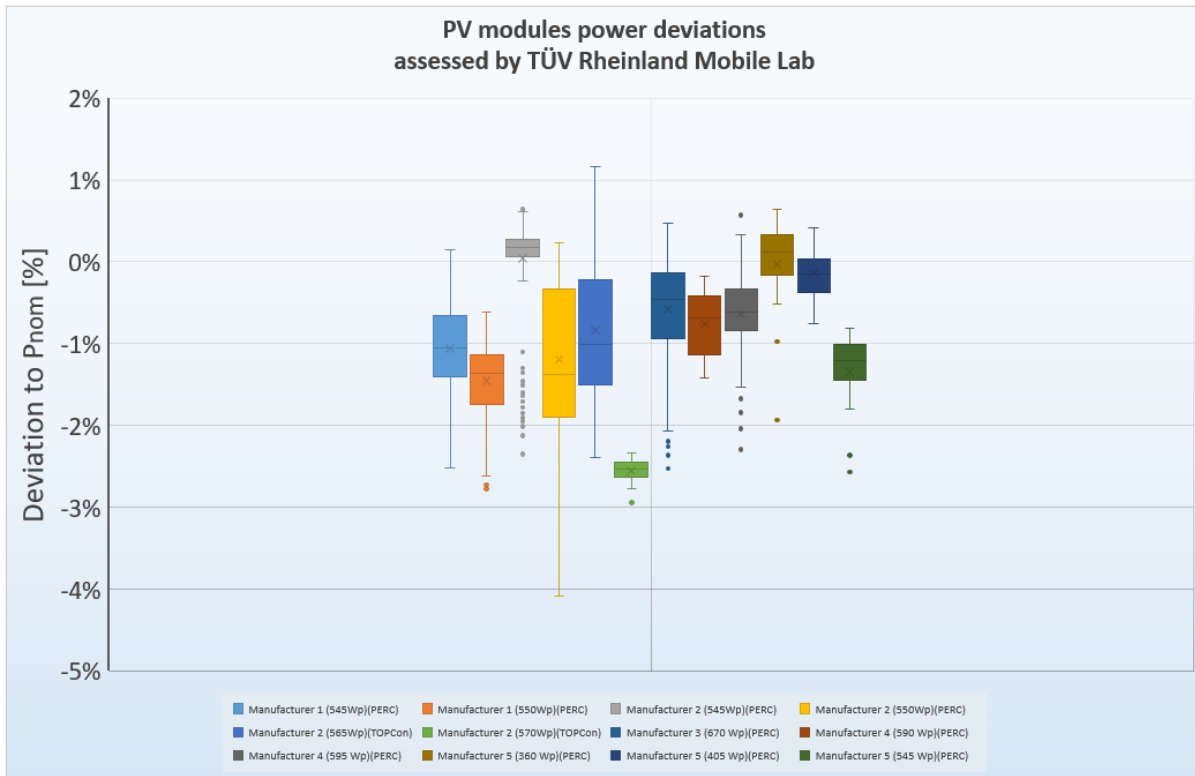


Figure 18: Power deviations of 4000 modules measured on-site with the mobile lab (P_{max} MU: 2.7% k=2).

The electroluminescence image below (Figure 19) revealed two cracked half-cells within a PV module, likely resulting from mechanical stress or impact during transportation [59]. The crack is evident through EL patterns, which indicate interrupted electrical conductivity and potential hotspots. This damage can affect the module’s overall performance, leading to reduced energy output and potentially accelerating degradation if not addressed promptly. The identification of such defects underscores the importance of rigorous transport handling protocols and post-transport inspections.

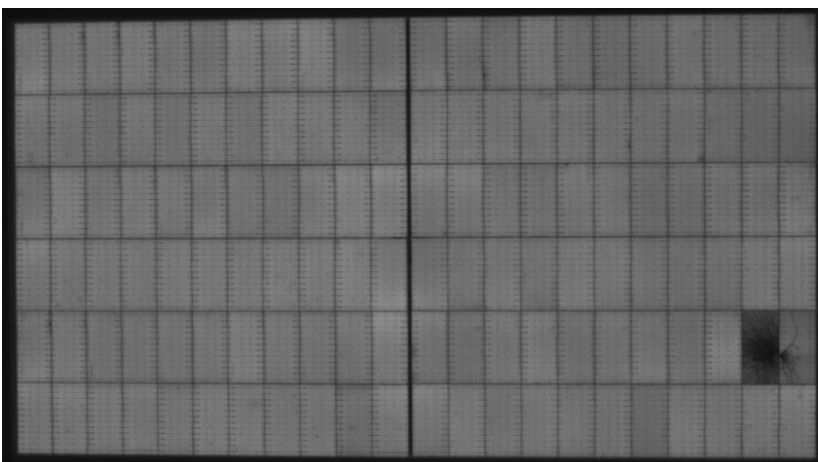


Figure 19: Example of damaged PV module after transport.



4.1.3 Cost-benefits of on-site testing

Post-shipment tests conducted using a mobile laboratory provide an additional representation of the module's performance. These tests identified changes in quality throughout the production process and at different manufacturing sites, as well as damages incurred during transportation, reinforcing the critical importance of comprehensive quality control procedures in maintaining the performance and reliability of PV modules.

Suppliers and installers of PV modules no longer need to transport their modules to a laboratory; instead, a mobile lab on-site can offer thorough testing services right at the module location. Particularly in the case of larger solar parks, where batch testing can involve more than a thousand modules, significant time, testing, and shipping costs can be saved. With conventional testing methods, which include disassembly and transport to a stationary laboratory—this process would take several weeks. However, post-shipment testing with the mobile laboratory takes only a few days, with a measurement output of approximately 100-150 PV modules per day.

From a financial viewpoint, the mobile lab also demonstrates significant cost-effectiveness. The overall expense for power measurements including EL measurements with the mobile lab ranges from 2000 € to 3000 € per day. In comparison, performing the same tests at a stationary laboratory would cost around 20,000 €, not even accounting for transport costs. Consequently, the expense at a stationary lab would be nearly 10 times higher. This efficiency does not make stationary laboratories obsolete, since many preliminary tests require specialized equipment such as climate chambers, hail machines, or mechanical load test stands. Nevertheless, regarding randomized batch testing, the mobile PV laboratory concept provides a cost- and time-effective alternative.

4.2 Underperforming of Roof Tops PV Installations – Optimizing Planning & Design Review

4.2.1 Current practice

Rooftop installations suffer from energy losses. Although the technology is mature and efficient, failures do occur, either due to early failure of key elements at the beginning of their useful life, wrong design and wrong selection of components, damage caused during logistics and installation, or damage due to poor (non-preventive) maintenance. The failures may impact differently a rooftop installation than a commercial power plant, but the source of failure may be very similar. Energy losses can have different sources; in general, they are aggravated by maintenance delays or non-preventive maintenance. Among other, the most common problems are early failures of PV panels, batteries or inverters, caused by manufacturing errors, logistics, improper installation, or damage under real operating conditions, or even acquisition of bad quality equipment, with limited warranty.

The exponential growth in rooftop solar installations, driven by rising electricity prices, represents an enormous challenge in rooftop PV installations. Today, there is still an enormous lack of experienced technicians, proper design and planning in many residential installations, resulting in low-quality systems and reduced performance; there is insufficient attention to shading analysis, roof structure capacity, and the selection of components suited to specific climates; monitoring by local power distribution companies is often averaged, leading to inaccuracies in understanding energy performance.



While the solar industry follows several quality standards, costs remain the main driver over quality. Local authorities oversee and review solar installations, but some, such as off-grid systems, may not undergo any formal inspection. In these cases, the client plays an important role in selecting a correct and professional installation company.

One of the main challenges worldwide is the lack of qualified and trained personnel for installing solar power plants and rooftop installations. New companies appear every year promoting a highly competitive market, which represents a risk for the quality, durability and lifetime of the power plants. In some cases, installation companies are composed of low-cost labour, inexperienced or uncertified electricians, unpaid interns or students, or even people without legal documents.

Furthermore, each year new components appear on the market, requiring highly qualified personnel who stay up to date with the final advancements and technologies, which is rarely the case.

Projects start at the early development phase before EPC and on-site activities. At this stage, profitability is a key factor for stakeholders and owners, which is natural in a competitive market. Therefore, all costs and potential risks should be carefully assessed. At this stage, it is of paramount importance to ensure the correct selection of high-quality components and a reliable EPC company to safeguard the project's long-term success.

4.2.2 Best practice

Most failures could be prevented through an optimized planning and design phase during construction of a power plant. Once the plant is in operation, failures come with significant costs and require urgent action, often involving the deployment of highly trained personnel, usually over long distances and to remote locations. During this process, both time and energy production are lost. OPEX generally does not account for these extra activities, which can place a heavy burden on maintenance teams. Specialist technicians are expensive, and after-sales service can become a risky aspect of the business.

During the design phase, the best practice is to emphasize quality over cost when selecting components, especially for challenging environments, such as coastal regions or areas with extreme weather. Before installation, it is of paramount importance to conduct comprehensive site assessments, including shading analysis, structural capacity, and accurate solar resource assessment. For the selection of components, it is important to follow standards and quality requirements and acquire that equipment from reputable suppliers. PV panels manufactured by the following standards such as IEC 61215 (performance and durability of PV panels) and IEC 61730 (safety and risk minimization) are a must.



Figure 20: Solar panels installed on a mediterranean-style flat plane roof in Peñalolen, Santiago, Chile. Enough space is found available for maintenance (Source: Solar Fotovoltaica Chile).

During construction and engineering, fostering better coordination between design, engineering, and installation teams is essential to minimizing risks introduced during project handovers. This helps prevent common design mistakes such as incorrect yield assessments and suboptimal placement of PV panels. Other best practices include implementing real-time monitoring to track energy production and consumption, optimizing load scheduling, and identifying issues early. Additionally, integrating advanced software solutions for accurate performance data and predictive maintenance, and ensuring adherence to country-specific regulations for materials and installation practices helps to mitigate risks from strong winds, UV exposure, snow, or hailstorms. PV systems should be designed to last at least 25 years. The following key performance indicators should be considered during the planning and design phases of such projects. Common failures found in local residential installations result from inadequate system design.

Roof structure capacity: a stable roof under the current building standards will allow a firm and durable solar structure over the years. Incorrect evaluation of the roof's structural capacity can lead to excessive loads, causing damage to the building or failures in the PV system. Furthermore, different roof materials and roof structure have a direct impact on project costs. Depending on the roof structure, PV panels can be installed vertically or horizontally, influencing on the amount of structural support required. Finally, the design decision impacts on the maintenance of the PV plant, as projects require some space to perform maintenance regularly. Correct design ensures a smooth installation process and high-quality. Figure 20 shows an installation in Chile by Solar Fotovoltaica (www.solarfotovoltaica.cl).



Shading analysis: Shading is a critical factor in residential installations, as a poorly designed system can be affected by significant energy losses, especially in winter when the sun is lower in the sky. An incorrect shading analysis can lead to mismatched energy outputs due to partial shading from chimneys, trees, or neighbouring buildings. In some cases, solar panels may be installed at a tilt to optimize sun exposure, and in other cases they are mounted coplanar to the roof. In both cases, the optimal orientation is to position the PV panels perpendicular to the sun. However, for aesthetic reasons, some installations even have started installing PV panels horizontally even in higher latitude regions. While this approach can lead to a 3-5% annual energy generation loss, it allows for a higher number of panels to be installed within a given area [60].

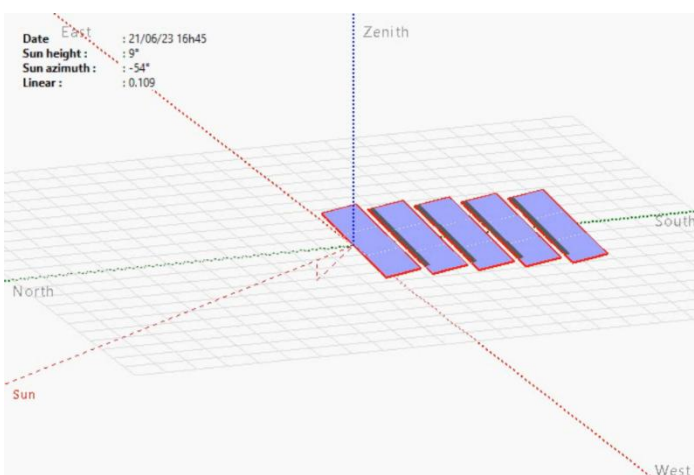


Figure 21: PVSYST shading 3D analysis of a plane (mediterranean) roof for a residential PV installation located in Vitacura, Santiago, Chile (Source: Solar Fotovoltaica Chile).

Choosing the right components for climate conditions: Choosing the right components for the climate in which the solar plant will operate, such as high temperatures or high humidity, or near coasts, is essential to avoid excessive performance degradation and failures. Solar panels are designed and tested under laboratory conditions that simulate real operating conditions. Among others, thermal cycles, humidity, impact of grains and others are simulated. Some standards used in the PV industry are the IEC 61215 that controls performance, reliability, and environmental durability of the PV panels, and the IEC 61730 that controls safety and risk minimization in PV module construction and use.

Monitoring: Accurate tracking of the energy produced and consumed is crucial to understanding the efficiency of a residential solar system. While local power distribution companies are required to measure energy consumption and injection monthly, these readings are often averaged rather than based on actual data. This practice can lead to inaccuracies in understanding system performance.

Comprehensive monitoring is essential not only for ensuring the proper operation and maintenance of the solar plant but also for optimizing energy usage by scheduling loads during peak sunlight hours. Real-time or detailed monitoring allows homeowners to maximize self-consumption, reduce reliance on the grid, and identify potential issues early, ensuring the long-term reliability and cost-effectiveness of the system.



In Figure 22, the hourly monitoring of a of 7.7 kWp rooftop installation shows that 16 kWh were produced on 20 January 2025 in summer in Santiago, Chile, covering 76% of the 22 kWh total daily demand for this house.



Figure 22: (left) Hourly monitoring of a rooftop installation; (right) the solar residential installation (Source: Solar Fotovoltaica Chile).

After the last natural disasters that struck Chile in June 2024, including storage to on-grid residential projects started to generate a strong interest. Solar on-grid inverters are mostly hybrid, allowing to add battery storage on the project. Figure 23 shows a 12 kWp project at 10:00 am 23/06/2025 in Chile, producing solar energy, charging the battery and the load; only a small part is required from the grid. Storage is programmed to feed energy to the load during night, and to remain a reserve in case of power outage.

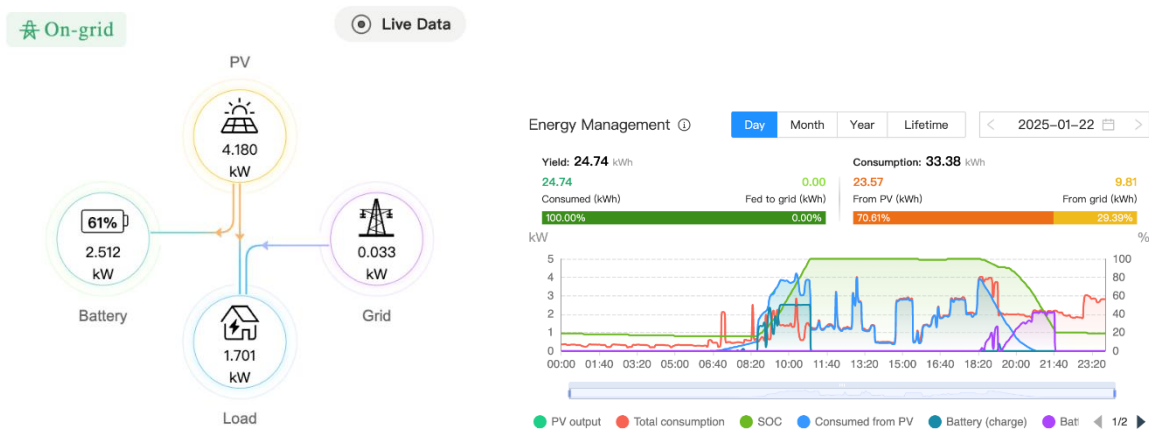


Figure 23: (left) Residential hybrid on-grid system; (right) Monitoring of a residential hybrid on-grid system.

Some common errors during design that impact installation are that most low-cost and fast residential installations lack proper design and planning. This significantly affects the quality of the project during installation, as installers are forced to make decisions based on budget constraints, low quality equipment or their own inexperience. Poorly designed projects often suffer from reduced performance, leading to increased maintenance requirements over time. Additionally, strong irradiance and UV can degrade materials used on rooftop installations (see Figure 24). Therefore, the local standards of each country should be followed strictly.



Figure 24: Solar cabling exposed directly to sunlight, compromising the whole project and even putting the property at risk. Incorrect use of conduit for transporting solar cables.

Strong climates, winds, snow and hailstorms put the PV installation at risk. If the standards are followed strictly, engineers can ensure the installation lasts for years.



Figure 25: The structure used for solar panels installation is crucial.

In Figure 25, it is shown how the structure used for solar panels installation is crucial. Strong winds exert impact on solar panels, creating a sail effect which is very dangerous, impacting surrounding areas, and putting the inhabitants at risk.¹

4.2.3 Cost-benefit analysis

As mentioned above, stakeholders can vary from project to project, and similar projects can experience different workflows; for a cost-effective project, it is important to map the different steps and KPIs of the workflow in a matrix with predefined stakeholders and value chain steps. This allows us to detect the responsibilities and the gaps to be reduced to achieve a high-quality and cost-effective project, with an extended lifespan.

¹ https://www.diariodecadiz.es/puerto-real/viento-arranca-solares-tejados-Casines_0_1765024297.html



Following the best practices and international and national (local) standards may ensure correct and optimized planning and design of rooftop PV installations. If a project is well constructed, the lifespan will be assured, bringing measurable financial, operational, and environmental benefits. Enhanced design processes and higher-quality components may mean an upfront higher costs, but it brings enormous benefits in the long-term, assuring performance.

Common failures, such as module degradation, inverter malfunctions, or structural damage, are often preventable through careful component selection, shading analysis, and structural evaluations during the design phase. In a well-designed project, maintenance and repair costs can be effectively controlled. Projects with a lack of design and planning often present early failures during the first two years of operation, and require urgent interventions, involving costly, specialized technicians and logistics. By addressing these issues pre-emptively, final customers and companies can minimize the frequency and severity of these interventions, leading to a reduction in OPEX, compared to those projects with early failures.

An early yield assessment is of paramount importance, as it ensures higher energy generation through improved roof selection, accurate shading analysis, and proper alignment of PV panels. We have found that an incorrect shading analysis can reduce system efficiency by 3-5% annually, translating into financial losses. Implementing precise tools like PVSYST for 3D shading analysis or selecting components suited to local climate conditions enhance energy output. As shown in our case study, for a standard 7.7 kWp residential installation in Chile, an improvement in energy yield of just 5% can result in an additional 400 kWh annually, equating to approximately 88 USD in annual savings for homeowners, assuming 0.22 USD/kWh in Chile.

Longer System Lifetime and Asset Value Ensuring that components are carefully selected and installations follow international standards, such as IEC 61215 and IEC 61730, can extend the lifespan of PV systems beyond the typical 25 years. This longevity enhances the overall return on investment (ROI). For example, avoiding premature failures due to poor-quality components or improper installations can save thousands of dollars over the system's lifetime, maintaining the system's value and reliability. PV projects in Chile have an ROI from 2-3 years at industry or agricultural level (10 to 20 kWp) and an ROI from 3-6 years for residential projects (2 to 10 kWp).

A high-quality installation not only ensures safety but also minimizes insurance premiums and enhances homeowner confidence in the technology. This reliability also attracts investors who prioritize predictable cash flows and reduced operational risks.

During commissioning, clients should be instructed in the operation of the PV project and in reading the monitoring data. This brings confidence to the process, and the clients are well informed about the installation, the positive impact on their savings and their contribution to fighting climate change motivates them.



4.3 Soiling Assessment and Cleaning Optimization

4.3.1 Soiling and cleaning throughout the life of a PV power plant

The life of a PV power plant can be divided into three main phases: project development, design and construction, and operation.

During project development, the performance engineering team is responsible for assessing the likely future energy output of a new project at its exact location and in its environment. The goal is to have an accurate estimation of the typical future energy output after losses. In this phase, time constraints usually prevent carrying out a soiling measurement campaign or similar assessments. Consequently, and due to the lack of publicly available data, the team often resorts to a “guesstimate”—for instance, assuming a standard 2% annual soiling loss with no monthly variation. While this estimate may be reasonable for some temperate climates, it can lead to significant over- or underestimation of soiling risk in drier climates. Further it often ignores the possibility (and cost) of cleaning.

WATERFALL-LIKE CLEANING OPTIMIZATION DOES NOT SOLVE THE PROBLEM

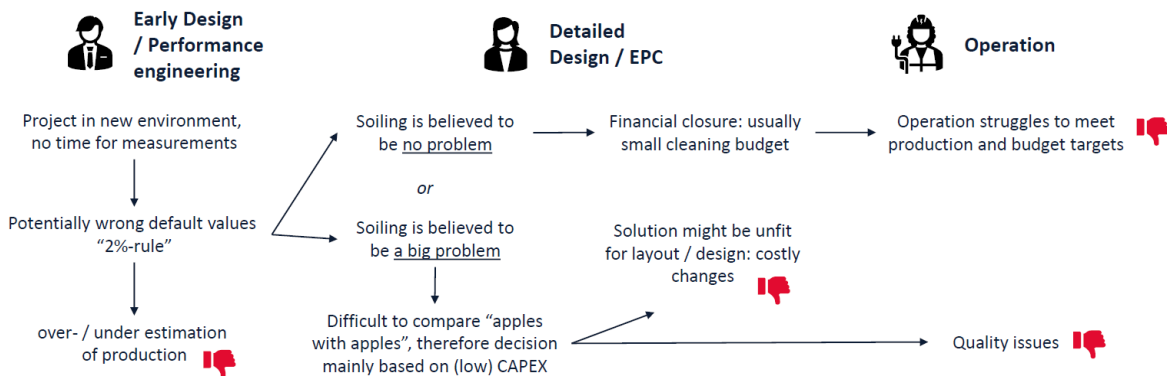


Figure 26: Potential consequences of failing to address soiling early through an integrated, iterative, and data-driven approach.

Once financial closure is achieved and financing is secured, the project transitions to the detailed design and construction phase, where the EPC team takes over. Here, the previously made assumption on soiling losses heavily influences project decisions. If soiling is considered a minor issue, the financial planning may include little to no cleaning budget, potentially causing the operations team to struggle with production targets later due to budget constraints. On the other hand, if soiling is considered a big issue, the EPC team may feel compelled to opt for an intensive cleaning strategy.

There are two problems that may arise from this:

First, without performing a holistic comparison of available cleaning solutions—ranging from manual cleaning (low CAPEX, high OPEX) to fully autonomous robots (high CAPEX, low per-cleaning cost, high frequency) and also including their technical parameters, performance and maintenance cost—the decision may default to (purchase) price alone, potentially resulting in a suboptimal solution that drives up costs or affects quality later on.

Second, the initial assumption (“guesstimate”) may turn out to be incorrect. This may happen during late design, construction or early operation (guarantee period). However, as the cleaning budgets have already been defined, it is usually very difficult to adapt the cleaning strategy



to a more cleaning intensive strategy, potentially resulting in substantial energy losses that could be mitigated cost-effectively.

In the operation phase, inaccuracies in soiling risk assessments from earlier stages can directly affect plant performance and costs, presenting ongoing challenges for the operations team. Without robust data or soiling measurements, plant operators often rely on visual inspections and subjective judgment—such as whether the modules “look dirty”—to decide whether and when cleaning should be carried out.

Even if a thorough, data-driven soiling assessment was conducted during development and design, installing soiling sensors is highly recommended to follow-up and fine-tune the cleaning strategy, particularly when the historical analysis shows that the optimal number of cleanings in each year is very variable, for example southern Europe. In regions like deserts, where cleaning is essential and must be performed almost continuously, soiling measurements may be less critical for planning the cleaning itself but remain highly valuable for performance monitoring and PR correction.

4.3.2 Best practices for soiling assessment and cleaning optimisation

The best practice for addressing soiling risks involves iterative and multidisciplinary optimization, integrating robust modelling, data analysis, and collaboration among stakeholders throughout the project lifecycle.

Baseline soiling risk profiles should be calculated using long-term meteorological and particulate matter data. Used soiling models should be validated and optimized based on available measurement data for the same, nearby or similar locations. This ensures that early-stage estimations are grounded in historical environmental conditions specific to the project location, providing a reliable foundation for subsequent analyses.

Any scenario analysis should be employed to simulate various cleaning frequencies, technologies, and environmental conditions as the project design advances. This enables stakeholders to assess the potential impact of different strategies on energy yield and operational costs, ensuring that decisions are informed and tailored to the unique challenges of the site. Additionally, economic modelling should be conducted to evaluate the costs and benefits of proposed strategies. This modelling should account for operational expenses, recover revenue from reduced soiling, include maintenance and repairs and account for financial factors such as inflation and financing rates, ensuring that solutions are both practical and economically viable.

By applying these best practices, soiling risk management becomes significantly more accurate and efficient. Using historical and site-specific data ensures precise soiling loss estimations and tailored cleaning strategies that align with the unique characteristics of each project. Economic modelling delivers clear insights into the financial implications of different cleaning schedules, enabling the identification of strategies that maximize energy production while minimizing costs. A centralized tool, such as PVRADAR, can help to streamline data integration and stakeholder collaboration, ensuring efficient and early decision making.



4.3.3 Key drivers, economic considerations and uncertainties for soiling-related decisions

The decision on the cleaning schedule depends on the assessment of additional costs related to O&M and the revenues achievable through the recovered energy [61]. Therefore, it requires an understanding of (i) the energy losses associated with soiling, and (ii) the economic value of the produced or missed energy [62]. However, these decisions are becoming increasingly complex, as operational constraints and market-related factors, such as electricity prices, clipping, and curtailment, now can limit the positive benefits of cleaning operations, and, therefore, their viability (Figure 27).

The first step toward the cleaning schedule decision requires estimating the accumulation of soiling and its effect on the modules' energy yield, which still remains a challenging task [63]. Traditional models assume a sawtooth soiling profile, characterized by alternating soiling deposition periods and cleaning events. The rates at which soiling deposit have often been estimated from the airborne particulate matter concentration, while cleaning events are typically associated with rain, often considered the only natural cleaning agent [64], [65]. However, the correlation between particulate matter concentrations and the deposited mass of soiling still needs to be improved, as the composition and the characteristics of airborne particulate matter can vary significantly with time, and its deposit rate likely depends also on conditions such as wind patterns, and humidity. Additionally, whether rain is sufficient to clean PV modules also depends on several factors [66]. In some cases, it can be effective, particularly when there are low mineral dust and sufficiently frequent rainfall. In other cases, wet deposition mechanisms can lead to the formation of strong, hard-to-remove bonds between the particles and the module's surface, which reduce the cleaning effectiveness of rain.

Even though traditionally mainly based on soiling accumulation and energy yield, soiling decisions have nowadays to account also for additional operations and market-related factors. These include, for example, the effects of clipping, curtailments, and low, if not negative, electricity prices. Clipping refers to the reduction of power output happening when the PV modules exceed the inverter's capacity [67], while curtailments occur when grid operators impose limitations on the amount of energy that can be injected into the grid [68]. In such cases, despite being produced by the modules, the energy cannot be sold and thus does not generate revenue. This means that, even if soiling is present on the modules and is reducing energy yields, the effects of cleaning actions would not be noticeable during periods of clipping and curtailment, as the extra energy recovered from cleaning would not be anyway injected into the grid. Therefore, clipped or curtailed energy does not contribute to offsetting the additional costs incurred by cleaning. For this reason, it is essential to estimate the occurrence of such events to determine when soiling ultimately results in revenue loss and when its effect is masked, rendering any mitigation actions ineffective.

In addition to the amount of recovered energy, the viability of cleaning also depends on the economic price at which energy is sold. In many markets, electricity is traded in bid-based markets, where the price is set hourly depending on the demand and the amount and cost of available energy. While traditionally set by costlier conventional energy sources, the market prices of electricity are now dropping during the central hours of the day, driven by the growing contributions of low-marginal-cost renewables (such as PV). Some countries are also experiencing negative electricity prices, meaning that electricity producers must pay to provide the grid with the produced energy. This further complicates the assessment of the economic viability of cleaning operations, as producers must carefully balance the cost of cleaning with



realistic expectations of the revenues associated with credible estimations of the actual energy recovery.

Factors influencing the cleaning schedule

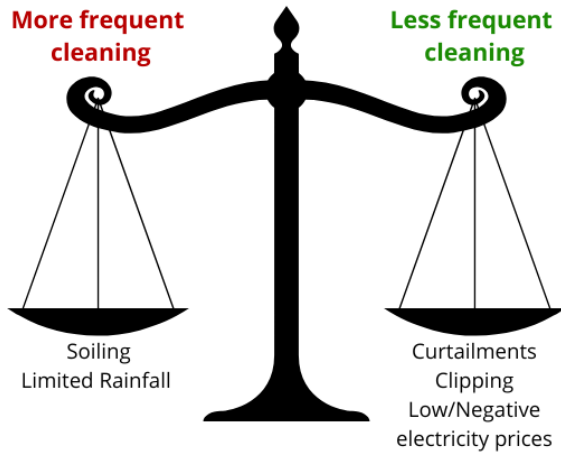


Figure 27: Factors influencing the cleaning schedule decisions.



4.4 Data-driven Corrective and Predictive Actions

4.4.1 Current practise

The operational phase of a PV project or a PV fleet involves multiple stakeholders such as field technicians, managers, technical and financial asset managers, and asset owners, among others. The activities carried out in the field must align with the interests, timeline, and budget of each party and the interaction must be as smooth as possible to ensure the optimal payback return of investment. For this reason, the need for a common source of truth with centralized and scheduled field activities and performance assessments transparent enough for everyone to understand is a must for a successful project.

One approach that is taking more attention is the usage of specialized software and data-driven solutions that will process millions of data points from loggers and SCADA not only to compute meaningful metrics but also to trigger corrective and predictive actions automatically. Those actions should then be acknowledged and attended to in a timely manner, preventing and optimizing performance.

Implementing an automated approach based on operational data may require an initial adaptation phase to complement the standard operating procedures. In the long term, however, it enables scalable and optimized management of solar PV assets.

4.4.2 Best practise

After the processing of algorithms for data cleansing, sensor check or loss breakdown, among many others, the solution can trigger corrective and predictive actions, where:

- **Corrective Actions:** As the name indicates, those actions are triggered to address issues that has been identified from the operational data. These are based on events that have already occurred.
- **Predictive Actions:** These types of actions will cover events that have not happened yet, and from this, the term « predictive » will be used. Based on the knowledge of the assets, together with weather forecasting data or KPI projects and pattern recognition, algorithms will be able to recommend actions in the future, allowing better planning and scheduling for O&M teams.

Either corrective or predictive actions can be related to any device within the PV system, including **inverters**, **strings**, combiner boxes, tracker units, or even weather station sensors. Those types of actions can be complemented with preventive, planned, or warranty-related activities.

Data-driven metrics for Corrective Actions

The accuracy and reliability of corrective actions depend on factors such as data integrity, data availability, and simulation approaches to compute expected power, among many other metrics. Having a clear performance loss breakdown at any given time is crucial to first identifying the root cause at a given device and then offering solutions to optimize yield and revenue. As displayed in Figure 28, together with specific device impacted, the recommendations should attach information that will help the O&M managers to acknowledge and coordinate the action based on (but not limited to) the following parameters:



- **Action Cost:** estimated cost of the action that may include labour hours, operational costs, or equipment replacement.
- **Weekly Impact:** estimated cumulated energy and monetary impact derived from the PPA schema, energy yield simulations and loss breakdown analysis. Grouping weekly will help O&M teams to understand better the impact of problems in a typical temporal window for teams to react and fix.
- **Payback Time:** the ratio of the energy yield being lost and the estimated action cost. This metric will help the O&M teams to prioritize their actions. This metric is of even higher importance when managing multiple PV assets at the same time.

Historical of Corrective Actions per inverter

Search: Event Description or Code Group by Site / Code Open in Event Operations

Object	Code	Description	Start date	End date	Payback Time (Weeks)	Weekly Impact (kWh)	Action Cost (Currency)	Weekly Impact (Currency)
> Solar Demo Spain	6019	[SAI] VAr support affecting energy production	4 May 01:00:00	27 Jun 01:00:00	0.0	336.8	0.0	16.8
> Solar Demo Spain	5008	[SAI] Grid curtailment	28 Apr 01:00:00	27 Jun 01:00:00	0.0	11847.1	0.0	592.4
> Solar Demo Spain	5016	[SAI] Inverter Unavailable Data	25 May 01:00:00	25 May 01:00:00	0.0	0.0	0.0	0.0
> Solar Demo Spain	5012	[SAI] Inverter efficiency outlier	25 Apr 01:00:00	27 Jun 01:00:00	6.8	10616.5	800.0	530.8
> Solar Demo Spain	5011	[SAI] Inverter efficiency decreasing	30 Apr 01:00:00	27 Jun 01:00:00	0.7	22471.8	800.0	1123.6
> Solar Demo Spain	5013	[SAI] Inverter Partial Capacity	23 Apr 01:00:00	25 Apr 01:00:00	20.8	769.6	800.0	38.5

Load more

Figure 28: An example of a dashboard indicating corrective actions with specific start and end dates, payback times, weekly energy, monetary impact, and action costs (courtesy of Univers Bazefield).

Upward performance extending waterfall analysis

Waterfall analysis is a widespread representation of the performance and financial status of a PV system. This type of tool offers a rapid visual understanding of the issues and is also a robust way to have a wide view of PV performance.

An example from a commercial analytics application is shared in Figure 29, starting with the analysis of budget data, such as P50 production based on Typical Meteorological Data (TMY) used and resulting from the PV design and financing phase. Both P50 and TMY are data that might not cover the actual reality of the asset due to asset upgrades or issues and climate variability; thus, correcting those values to match the current weather conditions is a must.

Then, the actual performance, divided into different categories like soiling, shading, and curtailment, will be compared with the budgeted performance assumed during project financing and annual planning. Many authors have reported that most of the assets globally are underperforming; thus, the waterfall typically goes down significantly.

The addition of data-driven solutions that can recommend actions will help asset managers optimize performance by scheduling field activities such as repairs, setting configurations, maintenance, or device replacements.

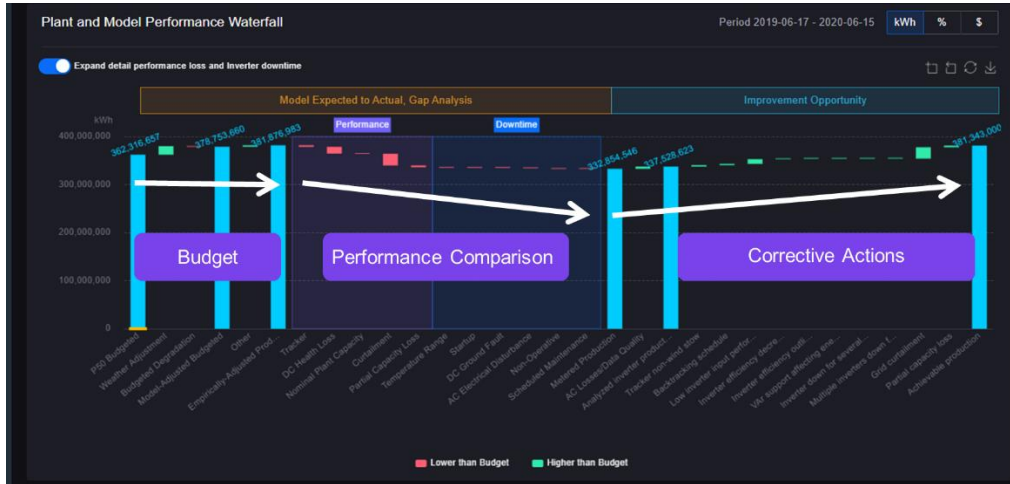


Figure 29: Waterfall Analysis that includes budget analysis, comparison of the actual and budgeted performance, and potential improvement opportunities via data-driven corrective actions (courtesy of Unifers Bazefield).

Proactivity with predictive actions

Predictive actions are based on the estimations of certain metrics towards the future, which can be based on weather forecasting, KPI projects, or pattern recognition techniques. Such actions aim to alert and prevent underperformance events, helping operators act in a timely manner before the event hits the assets and ensuring long-term reliability. The caveat of predictive actions is undoubtedly the possibility of false-positive events that could negatively impact the OPEX of a PV system; for that reason, the predictions have to be backed up by additional information, such as the probability of occurrence, together with the short- and long-term potential risks.

Figure 30 displays a simple example of predictive actions that were raised on 4 October 2024 for a PV plant located in Spain. The « High Wind Speed Detected » action is triggered due to forecasted wind speeds exceeding 23 m/s in two different periods.

Predictive Events Detected via Solar AI Analytics

Object ↑↓	Code ↑↓	Description ↑↓	Start date ↓↑	End date ↑↓	
Solar Farm B	70002	[SAI] High Wind Speed Detected	10 Oct 14:19:03	11 Oct 14:19:03	Open in Event Operations
Solar Farm B	70002	[SAI] High Wind Speed Detected	6 Oct 14:19:03	8 Oct 14:19:03	Open in Event Operations
Solar Farm B	70002	[SAI] High Wind Speed Detected	26 Sep 14:19:03	27 Sep 14:19:03	Open in Event Operations
Solar Farm B	70002	[SAI] High Wind Speed Detected	26 Sep 14:19:03	26 Sep 14:19:03	Open in Event Operations

Figure 30: List of predictive events detected (within the next 2 weeks) on 4 October 2024 for a PV system in Spain (courtesy of Unifers Bazefield).



The seasonality of corrective actions

One of the articles in the Solar Risk Assessment report by kWh Analytics 2024 identified the seasonal trends in data-driven corrective actions across over 300 solar sites, involving 28,000 devices and 11 GW capacity. Throughout 2023, a clear seasonality was noted: winter (December-February) sees a 14% increase in corrective actions compared to summer, with January and February each exceeding 60,000 corrective actions. DC health issues, accounting for about 50% of total corrective actions, are prominent in winter due to conditions like low temperatures and snow. Inverters, comprising 15% of corrective actions, experience more issues in warmer seasons due to cooling system failures, while trackers required consistent maintenance year-round.

These findings suggest that O&M teams should prepare for increased DC Health corrective actions in winter by allocating resources and stocking spare parts. For summer, O&M teams should anticipate inverter-related issues and prepare replacement cooling components. This approach enables targeted, proactive maintenance, reducing environmental impact and enhancing solar system performance throughout the year.

Figure 31 presents the overall statistics presented in the study.

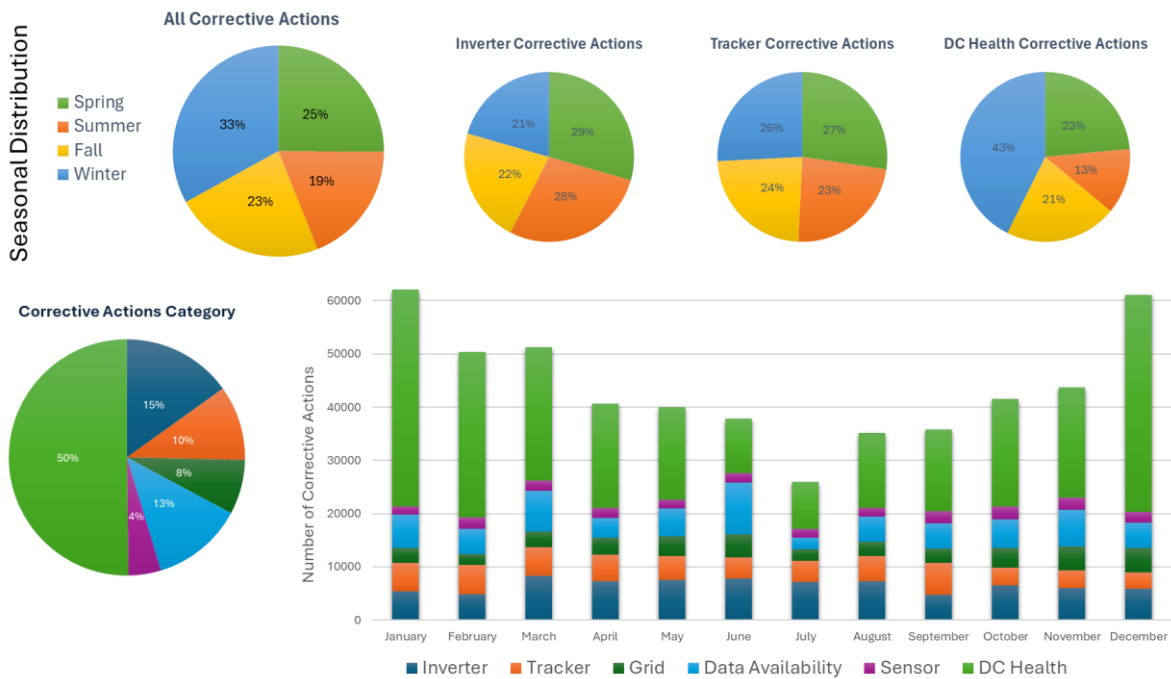


Figure 31: Corrective Actions Monthly Distribution and seasonal distribution for the main components in PV systems (Inverter, DC components and trackers) [kWh Analytics report].



4.5 Understanding Site Specific Hail Risk

Hail forms via accretion as convective storm updrafts carry water droplets into extremely cold areas of the atmosphere, where they freeze, grow, and increase in mass. Hail falls when the downward gravitational force exceeds the strength of the thunderstorm updraft. According to the U.S. National Weather Service, which is maintained by NOAA, the National Oceanic and Atmospheric Administration, severe hail is defined as having a diameter of more than 25 mm [69].

To meet the minimum ballistic-impact requirements in the IEC 61215-2 product qualification standard, PV module designs must withstand 11 impacts of a 25-mm freezer ice ball at terminal velocity [70]. As solar markets have proliferated globally, so have reports of catastrophic damage consistent with naturally occurring hail with a diameter of more than 25 mm.

Though hail-related insurance claims are relatively infrequent, hail damages are often far more costly than those associated with other types of claims. As an example, GCube's solar loss data for 2018–2023 shows hail accounting for 1.4% of claims volume (i.e., the total number of claims), but more than 54% of claims value (i.e., total incurred costs) [71]. Within this dataset, the four largest claims, which averaged \$56M each, were all the result of hail.

4.5.1 Hail risk mitigation

Project stakeholders can limit catastrophic hail loss events with improved technical literacy, due diligence, and risk mitigation practices.

- Hail risk to solar assets and portfolios is increasing due to a perfect storm of market and technology changes. On the technology front, PV systems are becoming more vulnerable over time as module manufacturers introduce larger format modules made with thinner front glass. On the market front, utility-scale project development activities are increasing in locations exposed to damaging hail.
- Technical advisors can use the return interval for naturally occurring hail to quantify hail risk meteorology on a site-specific basis. As a best practice, project stakeholders should require hail monitoring and tracker stow for utility-scale PV project sites where the return interval for ≥ 45 -mm hail (as determined by the 95th percentile largest hail diameter) is 100 years or less [72]. This conservative return interval threshold accounts for forecast uncertainties and climate change effects.
- PV module selection impacts solar power plant hail resilience or vulnerability. Module ballistic-impact resistance is a function of front glass thickness and heat strengthening [73]. Module packaging and cell technology influence resilience to power degradation due to cell cracking. Module size, frame, and mounting also impact probable hail losses.
- Single-axis trackers can significantly mitigate hail damage. Intelligent and proactive tracker controls can reduce the number of direct normal hail impacts and increase the number of glancing blows. Mitigation will vary based on the tracker's maximum tilt angle.
- In large utility applications, qualified technical advisors should quantify probabilistic financial loss levels over event recurrence intervals required by insurers (e.g., 500-year event) and typical investment hold periods (e.g., 10-, 20-, and 40-year hold). The goal of these loss studies is to provide comparative probable maximum loss and average annual loss values based on site-specific meteorological characteristics (e.g., historical hail event size and frequency) and project-specific technical considerations (e.g., PV module glass thickness and strengthening, tracker stow angle, and so forth) [74].



- Though severe hail is inevitable in some locations, large project losses are not. Post-event forensic investigations indicate that defensive stow protocols have successfully prevented widespread physical damage during severe hail events.

4.5.2 Hail defence case study

In mid-March 2024, a series of severe convective storms caused catastrophic solar project hail losses to the Fighting Jays solar farm, located in Fort Bend County, Texas, south-by-southwest of Houston. According to subsequent insurance industry reports, total financial losses at the 350 MW-rated PV power generation facility were expected to far exceed the project’s \$50 million hail damage sublimit [75].

Though the catastrophic losses at Fighting Jays dominated post-event media coverage, the technical advisory firm VDE Americas conducted a forensic investigation involving neighboring solar farms also exposed to severe hail. The results of this work indicate that operational hail stow protocols—combining early weather alerts and proactive hail stow at a high tilt angle—are in fact an effective means of preventing solar module damage and large financial losses [76].

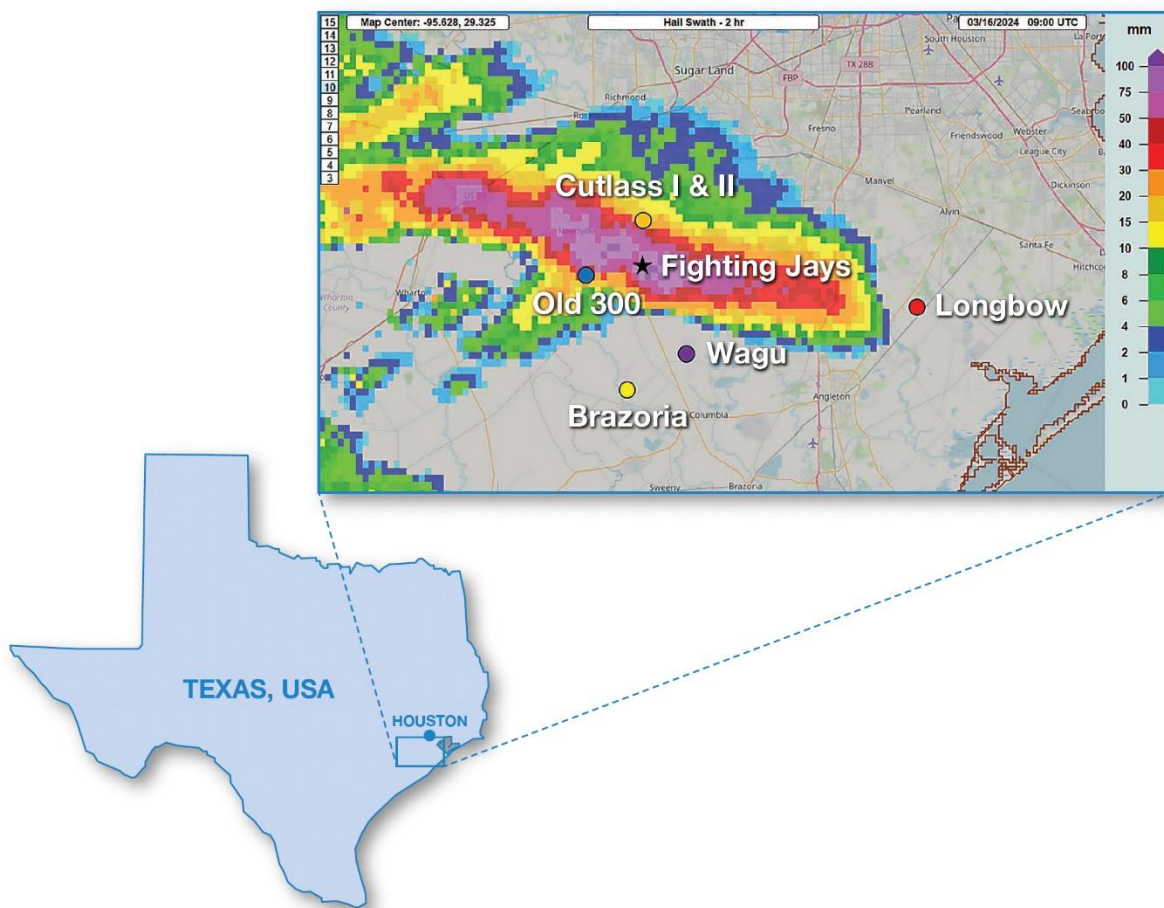


Figure 32: Operational hail stow protocols prevented project losses at three utility solar farms located within 15 km of the Fighting Jays solar facility [VDE Americas].



Specifically, VDE Americas studied the pre-event hail stow protocols and post-event damage reports for three utility solar farms located within 15 km of the hail-damaged Fighting Jays solar farm (see Figure 32). The following are high-level takeaways from VDE’s forensic investigations into hail damage to Fort Bend County, Texas, solar farms in March 2024 [77]:

- **Three severe hail producing storm events occurred within a 12-hour period.** To understand event meteorology, VDE reviewed NOAA’s next-generation weather radar (NEXRAD) data and analysed the maximum expected size of hail (MESH) in the Fort Bend County area around the time of the hail loss event [78]. This meteorological assessment determined that two major hailstorms occurred after noon on Friday, March 15, 2024. Additionally, a rare overnight hailstorm formed in the area in the early morning hours of Saturday, March 16, 2024.
- **All three of these hailstorms met >500-year event severity criteria.** VDE compared event-specific maximum hail size estimates to location-specific hail return intervals. The return interval metric characterizes the estimated amount of time between discrete events, such as the number of years between baseball-sized hail at a specific location. Comparing NEXRAD hail size estimates to naturally occurring hail return data in ArcGIS Online [79], researchers observed that the MESH values for all three of these severe storm events exceeded 500-year fixed hail return intervals for Fort Bend County, Texas. Specifically, meteorological models predict that the 500-year fixed hail return interval for the Fort Bend County area is ≥ 65 -mm hail. Based on this hailstone diameter threshold, all three of the severe convective storms on March 15 and 16, 2024, were 1-in-500-year events.
- **Four utility-scale solar projects were exposed to >500-year hail.** Mapping the path and intensity of all three severe hailstorms, VDE observed that the first storm’s hail swath had no solar farm overlap, whereas the hail swaths associated with the two subsequent storms crossed over four large utility solar farms—specifically, Fighting Jays, Old 300, Cutlass I, and Cutlass II. Studying the two storms with solar farm overlap, post-event meteorological analysis indicates that each of these four utility-scale solar farms was exposed to 1-in-500-year hail. In other words, VDE estimates that tennis-ball-sized hail or larger (≥ 65 mm) fell across some portion of four Fort Bend County-area solar farms.
- **Three solar farms withstood 1-in-500-year hail exposure.** Despite being exposed to >500-year hail, two of the four projects (Cutlass I and Cutlass II) sustained no direct hail-related damage. At the third site (Old 300), a few dozen modules sustained damage due to hail and wind-blown objects. Importantly, however, hail-related damage at the 270-MWp Old 300 PV project was limited to an area where a tracker motor issue prevented complete hail stow. Though the public record provides few details regarding the extent of the catastrophic damages at the fourth site-and no details about pre-event stow status-VDE has noted that the hail swath associated with the most severe hailstorm passed most directly over Fighting Jays. Specifically, MESH data indicates that the damaged solar farm was likely exposed to >100-mm hail, which the National Weather Service broadly categorizes as “giant hail” and “an extreme threat to life and property” [80].



Overview of damage reports and hail stow protocols

Fighting Jays

- Hail damage (no public details available)

Old 300

- Hail damage limited to ~40 modules on a non-stowed tracker (motor fault predated storm)
- <10 modules damaged due to wind-blown objects
- Oil gauge damaged on one MVT [medium-voltage transformer], causing inverter skid shutdown
- Modules stowed west, facing into the wind, per protocol and remained stowed overnight

Cutlass I

- No hail damage reported
- Stowed per protocol to nearest extreme angle
- Likely facing west for first storm, then facing east for next two storms due to night stow

Cutlass II

- No hail damage reported
- Project under construction
- Unknown portion of plant in hail stow per protocol.
- Stow direction unknown

Figure 33: Overview of 1-in-500-year hailstorm damage to utility-scale solar facilities in Fort Bend County, Texas, in March 2024 [VDE Americas] [81].

The field forensic results from Old 300, Cutlass I, and Cutlass II provide conclusive evidence that operationalized stow protocols are effective at preventing solar module glass breakage during a severe hail event. On the one hand, VDE found that PV modules in a hail-stow position sustained no direct hail-related damage from a 1-in-500-year hailstorm. On the other hand, VDE found a relatively modest amount of hail damage at a portion of the plant that did not achieve complete hail stow. Damage to unstowed PV modules clearly indicates that overall site losses could have been much worse if not for successful solar project hail stow protocols [72].

These real-world results validate outcomes long predicted by deterministic hail loss models, which consistently indicate that common sense hail defenses can prevent or mitigate hail-related damage. The Fort Bend case study is proof positive that even though severe hail risk is inevitable in some locations, large project losses are not. Forensic investigations show that operational hail stow protocols are effective for weathering 1-in-500-year severe convective storm events—even in the world’s most hail-exposed regions [77].

The findings in section 4.5 demonstrate that site-specific hail risk assessments and mitigation strategies, such as tracker stow protocols, are crucial not only for technical resilience but also have direct implications for insurance frameworks. Accurate quantification of hail risk and implementation of defensive protocols can significantly influence insurance premiums, coverage terms, and claims processing, helping asset owners to maintain insurability in high-risk regions. Moreover, permitting authorities may increasingly require robust hail risk management practices and documentation as part of project approval processes, ensuring that public safety and environmental compliance are upheld.



4.6 Financial Modelling and Investment Decisions for Utility-Scale PV Plants

This section discusses the impact of decisions on a range of economic KPIs, which are of importance for the overall valuation of a utility scale project before and after **Final Investment Decision** (FID). In the context of a FID, the word Final refers to the acceptance of the Financial Model (FM) and Business Case (BC) presented for acceptance or rejection (Decision) at the FID committee meeting. In this way, the decision refers to accepting the proposal or maybe deciding between a few optional concepts as presented. The iterative process of optimizing the proposal to be approved by the FID committee is conducted in advance and shall reflect an optimisation of the FM and BC to be presented. An optimisation could be the exercise when comparing two different solutions for PV module mounting are presented based on **Fixed Tilt** (FT) or **Horizontal Single Axis Trackers** (HSAT). Also, acceptance or questioning of analysis and assumptions prepared for the FID, in general, can be considered decisions, without which the project will not be realized.

So, the purpose of this chapter is to highlight and qualify the discussion of such impact factors, which through further data and analysis in a best practice approach can qualify the Final Investment Decision. Realization of utility scale PV projects may follow a general four step project model, starting with:

1. Screening of the site potential and constraints which may generate (conditionally) signed agreements with e.g. landowner(s),
2. Development of the project where local planning with the municipality is initiated and a dialog with the grid operator on grid access conditions is completed, followed by a
3. Structuring phase, where all key project elements including permitting, timelines and detailed plans for completion of **Engineering, Procurement and Construction** (EPC), project financing and electricity offtake will be prepared and presented in form of a business case quantified in a **Financial Model** (FM), for the project owner to make a (FID) for the project whereafter
4. Construction, energization and commissioning follow.

All analysis and decisions made up to the FID will impact on the attractiveness of the business case. This chapter presents and discusses some of the major decisions to be made during this process.

4.6.1 Current practices

At the time when all data, analysis and documentation for a FID is prepared, key technical decisions have already been made to ensure that the business case presented reflects an optimized PV project with respect to energy yield, land- and grid utilization as well as cost reduction.

Energy yield, energy density and energy cost optimisation

Optimizing the **Energy Yield Assessment** (EYA) of a PV installation involves a range of PV design parameters well known to most practitioners. For FT systems at higher latitude installations, it's about selecting a tilt angle which ensures the largest possible yearly generation potential considering also the negative impact of self-shading which will happen in case of the typical narrow distance between rows. The equivalent question when optimizing for installation of HSAT relates to limiting the need for backtracking required to reduce self-shading losses by



increasing the distance between rows – which then negatively will impact the deployment density for a given site area.

We hereby have introduced two primary KPIs for the Energy Yield optimisation exercise, in terms of the **Specific Production (SP)** in units of kWh/kWp and area utilization or **Power Density** in units of kWp/ha, from which we also can derive a secondary KPI as the **Energy Generation Density** in units of kWh/ha. Since both the specific production and specific mounting structure CAPEX measured in units of e.g. EUR/kWp or USD/kWp are quite different for the two technologies, it may be useful to introduce two additional KPIs in form of technology **Specific Energy Generation Cost** in units of EUR/kWh_{FT} and EUR/kWh_{HSAT} respectively which are often used parameters in a state-of-the-art PV project optimisation approach.

Total energy generation, project size and CAPEX

Although the units of Specific Energy Generation Cost are the same as for LCOE, it's important to distinguish between these, emphasizing that the specific energy generation cost does not include either lifetime generation, O&M cost, land lease nor financing cost.

By respecting that the context of the technology optimisation exercise is to provide input a FID, it's needed to increase the scope of analysis to the fully *sized* and complete technical solution, while not only considering the relative(specific) cost of two (or more) PV panel mounting solutions or other technology variations. This implies that the “hard” CAPEX besides the PV panel and substructure cost, must include all costs related to realization of the project inside the project boundaries which include all grid connection costs like MV cables, transformers, switch-gear and connection charges.

By sizing we refer to the total cost reflecting all installed DC and AC equipment. So although optimisation may have been performed considering the *specific* energy yield, *specific* energy density or the *specific* energy cost, it's imperative also to focus on the absolute **Energy Generation** in units of GWh, installed **DC-capacity** and **AC-capacity** in units of MWp and MW as well as total investment cost or **CAPEX** in units of USD or EUR, which may be substantially different whether a large FT or a smaller HSAT project is considered.

4.6.2 Best practice

Whereas state-of-the-art project optimisation constitutes a useful and relevant approach used to prepare for a standard FID, today's best practice needs to address the interests of several stakeholders including investors and financing institutions and their **Technical Advisors (TA)** in all detail.

The technical questions raised from these stakeholders will typically focus on revenue and risk reduction which goes beyond an interest in the estimate of generation potential (EYA) and general design considerations like site specific power and specific energy density, which already have been decided upon. During this dialog, decisions which impact the fundamental attractiveness of the business case of a utility scale PV project often relate to analysis and documentation which supports the decisions to select between FT and HSAT solutions as well as activities taken to reduce uncertainty and risks related to operating and financing the project.

Energy Generation Potential

When evaluating the externally prepared EYA, all model input parameters which reflect estimates and experience of the assessor may be challenged and detailed documentation and further arguments might be required or questioned by the TA. This might include assumptions on:



- Meteorological sources used and weighting among these sources,
- Transpositions model used,
- Module quality uplift as linked to flash data of manufacturing samples tested in a 3rd party test lab,
- Incident Angle Modifier as measured by the PV module supplier or an independent lab and provided in form of a pan-file,
- Assumptions on soiling- and snow-loss and use of spectral correction,
- First year degradation and availability assumptions

As these inputs to EYA are not based directly on scientific evidence or engineering methodologies, they are all candidates for discussion, before the parties may agree on a best estimate of the 1st year **Energy Generation Potential**.

Energy Export

For several reasons, the Energy Generation Potential cannot directly be used, when the more important project revenue shall be calculated. Both technical, operational, grid and market-related factors must be assessed, before the **Energy Export** (EE) can be estimated.

PV system degradation

As the revenue must be estimated over the full project lifetime of e.g. 30 years, an agreement on the expected **System Degradation** over this period must be made. Although the PV module manufacturer datasheet guaranteed power degradation-rate may be referenced, this number only reflects the PV module performance and is a guaranteed value which must be assumed to include a tolerance set by the manufacturer towards the expected degradation in various climates. Another approach could be to study historical PLR (<https://www.dnv.com/publications/dnv-views-on-long-term-degradation-of-pv-systems/>) covering a fleet of “old” systems.

By studying PLR of older fielded systems to make predictions of the PLR of systems to be installed nowadays, builds on the assumption that performance loss is a feature related to the technology in general, and will not be impacted on the actual cell and module architecture, Bill of Material and manufacturing maturity.

This is, however, hard to believe, since several of the technological upgrades introduced during the last years do address both the performance and long-term stability of the products. This is evident when we look at recent upgrades like:

- Change of silicon wafers from p-type to n-type wafers, which significantly reduces the degradation performance loss related to **Light Induced Degradation** (LID),
- Introduction of glass-glass modules, which impact the water vapor permeability and thereby performance loss related to metallization corrosion,
- Halving the size of cells to achieve low-current half-cell stringing design,
- Use of soldering robots and highly automated manufacturing lines for both solar cell and PV modules, which mostly takes place in newer high-volume factories designed based on many years of manufacturing focus and by applying best practice strategies in quality assurance and operational procedures.

Whereas a low degradation factor in the range of 0.25-0.3% p.a. may favour the project valuation positively, a higher degradation factor may be requested by the O&M provider (which in some cases may also be the EPC contractor), to facilitate meeting the operational performance warranties during the first year.



Grid related losses

In most parts of the world, grid capacity is a limited and/or expensive factor. In addition, the requirements of the grid operator for generators (inverters) guarantee technical capability for delivery of several kinds of system services like reactive power etc. to the grid are constantly increasing. For these reasons, the ratio between installed dc-capacity and a **Fixed Grid Agreement** or guaranteed energy export capacity is growing, which results in increasing inverter clipping losses.

Grid contracts based on **Flexible Grid Agreements** are also increasingly being concluded, whereby the project operator accepts that the required full grid export capacity may not always be available. Based on further information from the grid operator, it then may be required to estimate the duration, frequency and extent of the curtailment related to such a Flexible Grid Agreement, where:

- *duration* relates to the period of years, during which the flexibility may apply (e.g. until planned grid-enforcement is fully implemented),
- *frequency* relates to the expected number of hours per year where such a flexible grid agreement induced curtailment may be applicable (e.g. with an indication of up to 200 hours per year), and
- *extent* describes the degree of curtailment which may be imposed upon the project if curtailment is requested, as the curtailment may apply to all or only part of the installed capacity.

Market related adjustments

In several electricity markets, where deployment of renewable energy sources like wind and solar have gained substantial market share [82], the day-ahead electricity price includes an increasing number of hours with negative prices. Since utility scale projects only in extreme cases (old type of Feed-In-Tariff or Power Purchase Agreements) will be operated for energy export during such hours, it's necessary to assess and forecast this market development and decide on the associated risk of lost energy sale. As the hours with negative prices often coincide with hours of significant PV production, it's becoming essential to include such an analysis of **Negative Price Curtailment** for the specific electricity bidding zone into the forecasted energy export calculation.

As the technical capability of PV inverters and park controller systems as well as short- and long-term energy forecasting are improving significantly in quality and performance capability, utility scale projects may also participate in the ancillary service markets providing e.g. Frequency Containment Reserve (FCR). Whereas such market participation will be based on an owner's decision and assessment of a positive contribution to the business case, this participation will reduce the amount of energy made available for direct electricity sale, and as such constitute another element of correction known as **Market Activity Based Curtailment**, when adjusting the **Energy Generation Potential (EGP)** into an estimate of the net **Electricity Export** volume.

Finally, **Unavailability Loss** needs to be considered. Since this loss is assumed to be applicable randomly, the loss is typically included in the energy loss table, by a fixed availability assumption factor to be decided upon.

In Figure 34, the five adjustments introduced required to be applied to the Energy Generator Potential to obtain the net Energy Export are illustrated. The example is based on a 100 MWp generic Danish PV project connected with a maximum export capacity of 70 MWac and a Flexible Grid Agreement according to which, operation during the first four years is only



guaranteed for the 50 MWac whereby the remaining 50 MWac grid capacity may be subject to curtailment of up to 200 hours per year in this example - during hours where the grid may be congested. Further market-based curtailment during hours of negative electricity price has been addressed based on a forecast of power prices for the bidding zone DK2 and the yearly degradation rate has been set to 0.25% p.a. and an availability of 100% has been assumed.

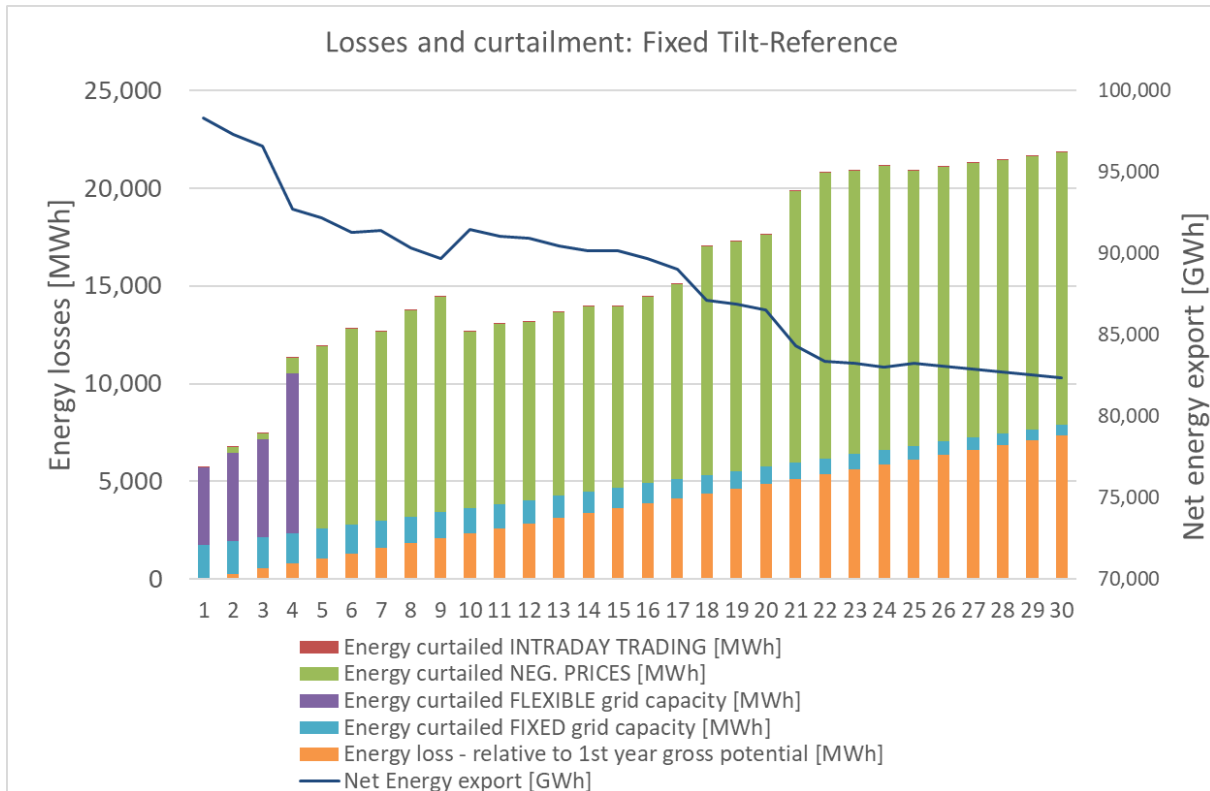


Figure 34: Losses and curtailment analysis.

Economic valuation of electricity generation

As penetration of PV generated electricity increases in most price bidding zones, a cannibalization of the generated-weighted **Captured Price** (CP) will develop which result in a reduction of the revenue over the lifetime of the projects. The direct impact of this cannibalization may be circumvented by entering long-term fixed-priced (pay-as-produced) **Power Purchase Agreements** (PPA) or from tendering in a subsidizing price scheme like e.g. **Contract-for-Difference** (CfD) for a part or all the generated volume. But since both the PPA off-taker and a government support scheme will need to reference the strike price to a market value of the electricity, it is necessary to analyse the expected value of the PV generation, referenced to an expected baseload market price.

The average yearly CP is calculated simply by multiplying the hourly generation profile with the hourly day-ahead market price and then dividing this revenue by the total Energy Export. Whereas math is simple, the challenge arises from the fact that we're dealing with often very uncertain forecasted generation and price profiles.

Such forecasted prices are generated by doing energy system modelling. This kind of modelling determines the amount of electricity generation capacity which is expected to be



constructed in any given market for the coming decades, based on an assessment of announced policy and regulations and estimated market-based profitability as seen by asset owners and investors.

As profitability obviously depends on the expected off-take, policy announcement for planned electrification actions must be incorporated in the energy system modelling.

Once the energy system demand-side load profiles and technology specific generator capacities have been determined, it's also possible to generate forecasted electricity price based on the marginal pricing principle, which are then used to also calculate the technology specific capture price. Nevertheless, the availability of such hourly forecasted power prices is essential for valuation and FID of the utility scale PV project, even if the forecasts can only be provided with large variability between scenarios. These variations reflect the uncertain nature of all assumptions related to the green transitions, where ambitious political targets on electrification and built-out of both *supply* in terms of e.g. **Renewable Energy** (RE) and *demand* in terms of e.g. **PtX**-facilities meet the actual policy implementation including political instability (reversal of targets) and real-world conditions e.g. interest rates, component price volatility and lack of installation professionals.

The character of this analysis uncertainty is illustrated in the example below, where the technology dependent yearly **Value Factor** (VF: capture price divided by the baseload price) is forecasted for a project period of 30 year based three different model scenarios of the energy demand development and energy system built out in Denmark and interconnected European countries.

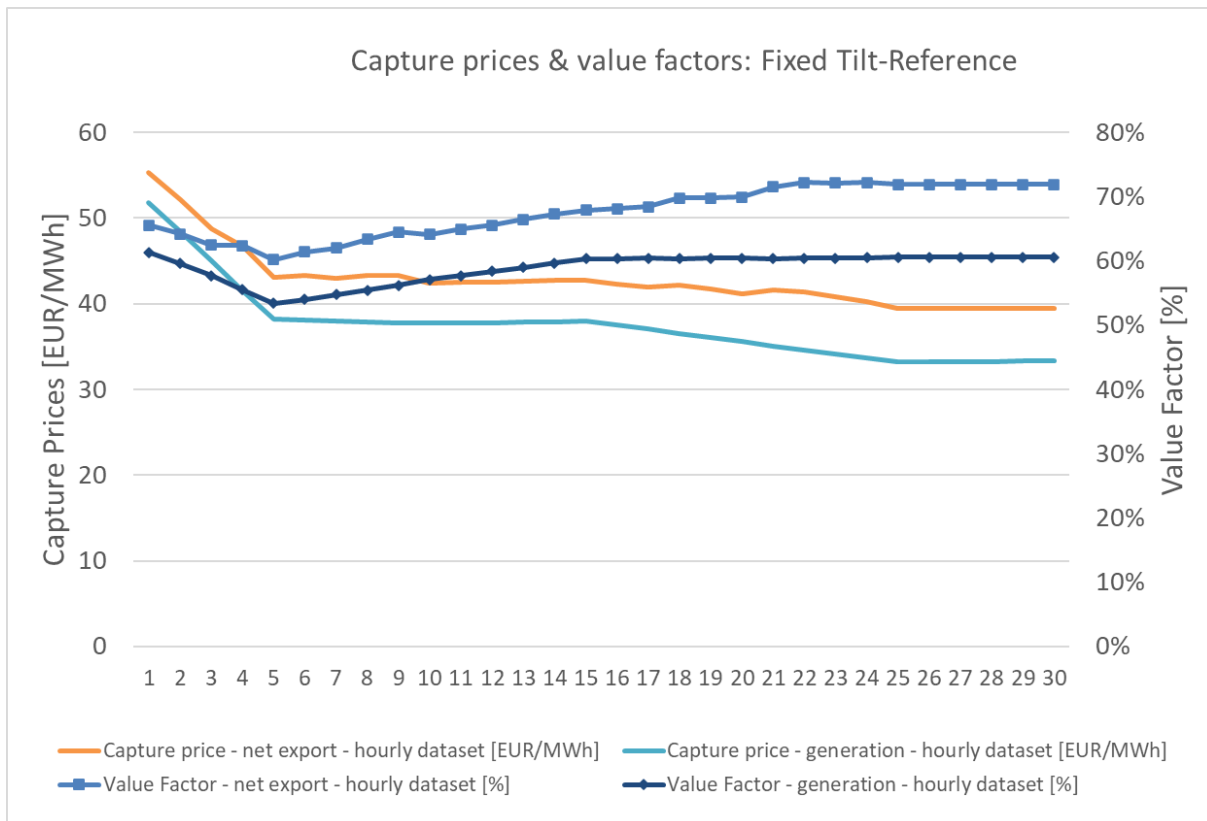


Figure 35: Capture prices and value factors.



Figure 35 not only differentiates between the Capture Price in units of EUR/MWh which reflect the absolute (uninflated) value of the electricity, and the Value Factor in units of percent which represents the Capture Price normalised to the forecasted power price used, but also discriminate between the Capture Price and Value Factor which is applicable to the Energy Generation Potential and the values which are relevant when focussing on the Energy Export. As we've learned in the previous figure, the Energy Generation Potential has to be reduced by between 6 and 25 GWh per year to reach the net Energy Export value, we need to be very clear in communicating if the specified CP and VF refer to the EGP (which are based on the EYA only) or if adjustment as mentioned above has been made to reach the more uncertain estimated Energy Export.

Figure 36 presents the lifetime average Value Factor for both Fixed Tilt and Horizontal Single Axis solutions for three different scenarios. These compare power prices in a reference scenario to a scenario where either the demand (PtX-delayed) or the consumption (RE-delayed) built-out is assumed delayed compared to the reference scenario.

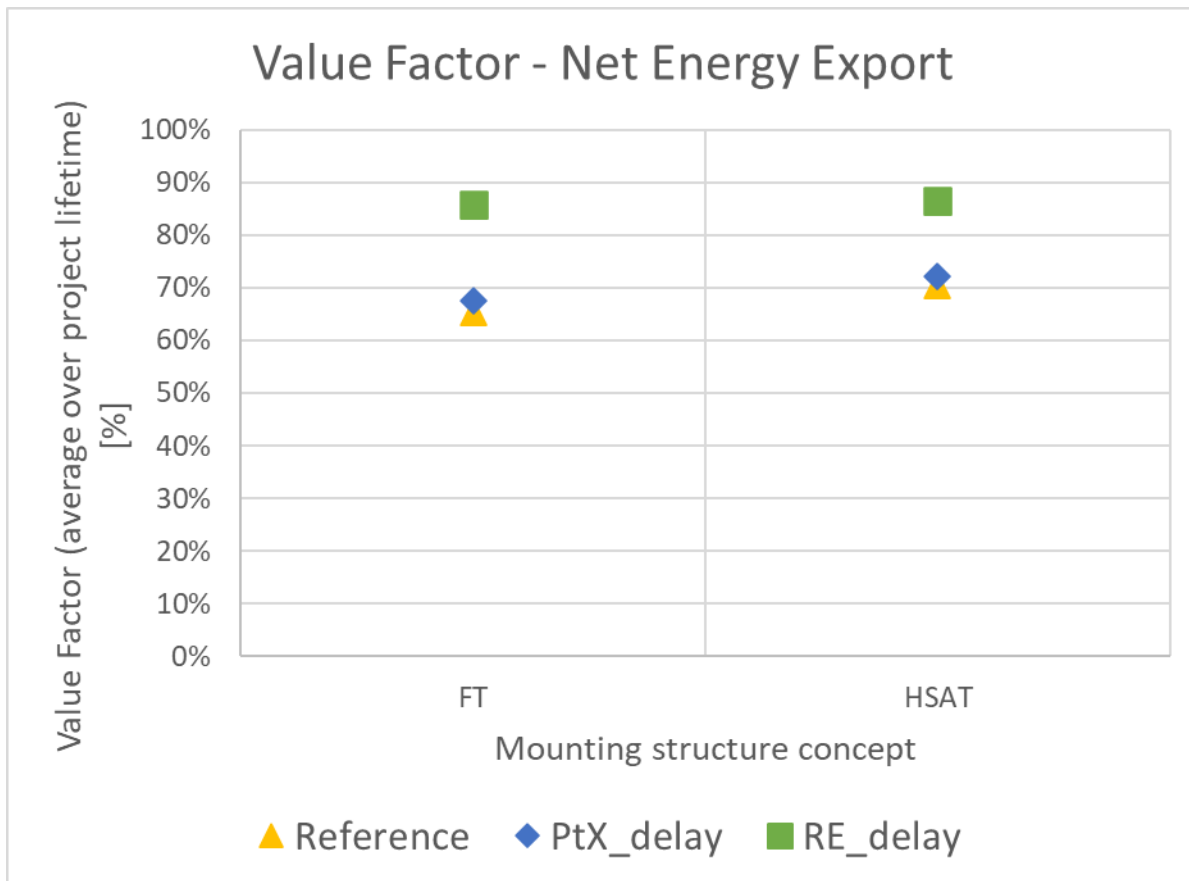


Figure 36: Value Factor for the net energy export from a utility-scale PV project located in Eastern Denmark in three different scenarios over forecasted power prices as given in the reference scenario, the PtX_delay or the RE_delay scenario.



From Figure 36, the decision for HSAT against FT is seen to improve the business case with a value factor uplift of 4.9% (from 65.5% to 70.4%) which reflects that more generation will be sold during higher priced hours for a tracker compared to a FT system. An equivalent level of uplift, however, cannot be expected in all scenarios, and in the PtX_delay scenario the absolute percentage-point gain in HSAT VF is only 0.7%p (86.5%-85.8%) in which case the VF only has a limited impact on the decision to use either FT or HSAT.



5 CONCLUSIONS

This report has demonstrated that technical and economic decision-making in PV projects cannot be treated independently: choices made at each stage of the value chain measurably affect key performance indicators (KPIs), risk exposure, and ultimately asset value. By combining a structured decision matrix, a KPI framework and application-specific case studies, the work provides an integrated perspective on how quality, performance and economic value are co-determined over the full project lifecycle.

The development of the decision matrix workflow has revealed critical insights into the complex interactions between stakeholders across the PV value chain. From banks and investors in the development phase to O&M operators in the operational phase, each stakeholder's decisions create cascading effects that influence project profitability, reliability, and sustainability. The mapping exercise demonstrates that quality gates implemented early in the value chain—particularly during development and engineering phases—provide the greatest cost-effectiveness in preventing downstream failures and performance losses. The exercise still shows large gaps in the feedback from relevant stakeholders where parts of the workflows are missing and must be subject to further work to cover the gaps.

The case studies presented demonstrate that proactive quality management delivers measurable economic benefits that far exceed the initial investment costs. Post-shipment testing with mobile laboratories, for instance, provides cost savings of nearly 10 times compared to stationary laboratory testing while identifying critical defects that could lead to significant performance losses. Similarly, optimized planning and design review for rooftop installations can improve energy yield by 5% annually through better roof selection, accurate shading analysis, and proper component selection, translating to substantial revenue gains over the system lifetime. The analysis of repair versus replacement decisions reveals that up to 50% of PV waste can be diverted from recycling into reuse through optimized strategies, significantly reducing lifecycle costs. However, these decisions require careful evaluation of testing costs, reliability expectations, and market conditions for reused components. The economic viability of such strategies is increasingly supported by evolving regulatory frameworks that mandate state-of-health assessments before premature disposal.

In the report, we highlight that the optimal decision-making strategies must be tailored to specific PV applications and geographic contexts. Bifacial tracking systems, floating PV, and agrivoltaic installations each present unique challenges that require specialized approaches to risk assessment and mitigation. The complexity increases in applications like agrivoltaics, where decisions must balance both energy production and agricultural yield objectives, necessitating integrated modelling platforms and multi-year performance simulations. Geographic factors significantly influence operational strategies, particularly evident in Australia where remote locations drive different approaches to spare parts management and maintenance scheduling. The seasonality of failure modes demonstrates the need for region-specific maintenance planning and resource allocation with a global analysis over 300 sites showing for e.g., DC health issues increased by 14% in winter and inverter problems prominent in summer.

The increasing frequency and severity of extreme weather events, driven by climate change, requires sophisticated approaches to risk assessment that move beyond traditional Gaussian assumptions. The analysis of hail risk mitigation demonstrates that proactive defensive strategies, including tracker stow protocols and appropriate module selection, can prevent catastrophic losses even during 1-in-500-year events. In the case studies, we provide compelling evidence that operational readiness and technology choices can mean the difference between



manageable maintenance and project-threatening losses. Financial risk models must evolve to incorporate climate-adjusted scenarios and account for fat-tailed distributions of extreme events. The introduction of concepts like Probable Maximum Loss and Average Annual Loss provides frameworks for quantifying risks, but these must be updated to reflect changing environmental conditions and emerging threats.

The transition toward data-driven corrective and predictive maintenance represents a fundamental shift in how PV assets are managed. The implementation of advanced analytics and automated action triggers enables scalable optimisation across large portfolios while reducing response times and improving cost-effectiveness. The seasonal patterns in maintenance requirements highlight the value of predictive approaches in resource planning and spare parts inventory management. The integration of real-time monitoring, weather forecasting, and pattern recognition algorithms enables proactive interventions that prevent performance losses before they occur. However, the success of these systems depends critically on data quality, sensor reliability, and the development of accurate models that account for site-specific conditions and equipment characteristics.

5.1 Recommendations for Industry Implementation

To maximize the economic benefits identified in this report, the PV industry should prioritize a set of concrete actions. Quality gains rarely come from a single actor; they rather emerge when each stakeholder owns its share of the value chain. The recommendations below are therefore grouped by the four stakeholder clusters with the strongest leverage over project outcomes. The decision matrix introduced in chapter 3 provides the shared workflow and vocabulary that make these recommendations actionable across the value chain.

5.1.1 Asset Owners and Investors

- Make quality KPIs contractual, not aspirational. Embed performance, degradation, and reliability KPIs into procurement specifications, supply contracts, and lender due-diligence checklists from project inception and thus not as post-COD audit step.
- Require independent verification before acceptance. Mandate post-shipment component testing, as-built engineering review, and site-specific risk assessment as gating conditions for COD sign-off and final tranche release.
- Price climate risk before Final Investment Decision. Insist on stressor-specific risk reports (hail, soiling, flood, wind, thermal) and ensure insurance terms reflect actual site risk distributions rather than portfolio averages.
- Fund the data infrastructure that protects the asset. Treat monitoring systems and analytics platforms as bankable CAPEX: the long-term benefits of reduced downtime, optimized performance, and refinance ability justify the initial investment.
- Use the decision matrix as a due-diligence audit tool. Verify that each stakeholder has demonstrably owned its activities at every phase, and that hand-offs between phases are documented against a common workflow.



5.1.2 Developers and EPCs

- Implement quality gates early. Concentrate technical due diligence, component testing protocols, and site-specific risk assessments in the development and engineering phases, where intervention cost is lowest and impact potential is highest.
- Specialize design for the technology. Recognize that floating PV, agrivoltaics, and bifacial tracking systems each carry unique considerations for design, operation, and maintenance. Generic design templates underdeliver in all three.
- Translate climate inputs into defensive design choices. Operationalize advanced climate-risk modelling into concrete decisions on module class, mounting, drainage, hail-resistant glass selection, and protective operating modes for high-risk locations.
- Document hand-offs against a shared workflow. Use the decision matrix to clarify roles, downstream impacts, and the activity-level inputs and outputs at every phase transition, particularly the engineering-to-construction and construction-to-commissioning gates.
- Negotiate in shared vocabulary. Adopt SOA / PBSOA classification and the matrix's activity descriptions when negotiating KPIs, scope, and warranties with owners, financiers, and O&M providers tranche release.

5.1.3 O&M Providers and Asset Managers

- Invest in monitoring and analytics for predictive operation. Build the data infrastructure that enables predictive maintenance, real-time optimization, and waterfall analysis of performance losses beyond reactive ticket-driven O&M.
- Apply technology-appropriate operational strategies. Tailor soiling, vegetation, tracker calibration, and inspection regimes to the specific technology and microclimate; generic playbooks miss material yield gains on tracking, bifacial, floating, and agrivoltaic systems.
- Make handover a structured artefact, not a paper exercise. Treat the matrix activity-level outputs as the template for commissioning hand-over packages, so operational baselines are unambiguous and disputes are minimized.
- Close the design-to-operate feedback loop. Provide structured failure-mode and performance-loss feedback to developers and EPCs, so design assumptions converge with operational reality across the portfolio.
- Translate field evidence into financial language. Convert degradation, availability, and energy-loss data into KPIs that owners and lenders can use directly for refinancing, repowering, and future project underwriting.

5.1.4 Policy Makers and Regulators

- Move best-practice guidelines from voluntary to enforced where bankability impact is demonstrated. The implementation gap (guidelines exist but are rarely mandated) is the single largest barrier identified in this report to consistent quality outcomes.
- Recognize SOA / PBSOA classification in standards updates. Avoid locking new installations into outdated practice by referencing the state-of-the-art and beyond-state-of-the-art distinction when revising codes, certification schemes, and tender requirements.
- Promote shared workflow ontologies. Endorse common value-chain workflows — of which the decision matrix is one example — so cross-stakeholder due diligence becomes auditable rather than narrative.



- Update siting and permitting requirements to reflect modern climate risk models. Outdated return-period assumptions and resource statistics are systematically under-pricing hail, flooding, and extreme-temperature exposure.
- Support open data and independent verification. Back initiatives that make yield, degradation, and reliability data structurally available, so third parties can verify claims and so newcomers, and new geographies do not need to relearn the same lessons.

5.2 Looking Forward

The photovoltaic industry's continued growth and maturation require increasingly sophisticated approaches to decision-making and risk management. This report provides a foundation for understanding these complex relationships, but the rapid pace of technological change and evolving environmental conditions demand ongoing research and adaptation.

The frameworks, case studies, and best practices presented here represent current industry knowledge, but they must be continuously updated to reflect new technologies, changing market conditions, and lessons learned from operational experience. The ultimate goal is to create a more resilient, efficient, and profitable solar industry that can deliver on its promise of sustainable, cost-effective renewable energy for decades to come.

If these developments are pursued in a coordinated manner, quality-driven decision-making can deliver not only lower LCOE and higher asset values, but also improved resilience, insurability and public acceptance. In this way, the PV sector can better fulfil its role as a cornerstone of a sustainable, reliable and economically robust energy system.



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